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Strength Regain of Damaged Bendable Composite with Carbon Fibre Reinforced Polymer Sheets

by

Saif ur Rehman Khalid

A thesis submitted in partial fulfillment for the
degree of Master of Science

in the

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Saif Ur Rehman Khalid

Abstract

Damage to bendable composite (BC) slabs can lead to a reduction in flexural load-carrying capacity and compromise their post-cracking performance. This study experimentally investigates the strength regain of damaged bendable composite slabs strengthened with externally bonded Carbon Fibre Reinforced Polymer (CFRP) sheets. The experimental program considered BC slab specimens with 1.0%, 1.5%, and 2.0% steel reinforcement ratios. The specimens were initially tested under flexural loading to establish their response and introduce a controlled damaged condition. The damaged specimens were subsequently strengthened using CFRP sheets and retested under the same flexural loading arrangement. The structural response was evaluated in terms of peak load, flexural stress, deformation, energy absorption, Flexural Toughness Index (FTI), strength regain, and failure behaviour.

The experimental results demonstrated that CFRP strengthening improved the flexural performance of the damaged BC slabs. Based on the measured peak loads and the strength-regain expression defined in Equation (3.2), the percentage increase in peak load was 29.80% for the 1.0% steel-reinforced specimen, 52.11% for the 1.5% steel-reinforced specimen, and 118.51% for the 2.0% steel-reinforced specimen. The corresponding peak loads increased from 20.10 kN to 26.09 kN for the 1.0% specimen, from 21.80 kN to 33.16 kN for the 1.5% specimen, and from 22.20 kN to 48.51 kN for the 2.0% specimen. The 2.0% steel-reinforced specimen exhibited the highest percentage increase in peak load within the investigated range. CFRP strengthening also increased deformation capacity and energy absorption, indicating improved post-cracking performance.

An empirical relationship was also developed using the experimental peak-load results to provide a preliminary estimation of the peak load of CFRP-strengthened BC slabs. The proposed relationship showed good agreement with the experimental observations within the investigated experimental range. Overall, the findings demonstrate that externally bonded CFRP sheets can provide an effective rehabilitation technique for restoring a measurable portion of the lost flexural capacity

of damaged bendable composite slabs while improving their post-cracking and deformation performance.

Keywords: Bendable Composite (BC), Carbon Fibre Reinforced Polymer (CFRP), Structural Rehabilitation, Strength Regain, Flexural Performance, Energy Absorption, Flexural Toughness Index (FTI), Peak Load Prediction.

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List of Abbreviations

ASTM	American Society for Testing and Materials
BC	Bendable Composite
CFRP	Carbon Fiber Reinforced Polymer
E	Total Energy Absorption
E_1	Energy Absorbed up to First Cracking
E_2	Post-Cracking Energy Absorption
ECC	Engineered Cementitious Composite
FRP	Fiber Reinforced Polymer
FTI	Fracture Toughness Index
kN	Kilonewton
mm	Millimeter
MPa	Megapascal
PCC	Plain Cement Concrete
PFS	Peak Flexural Stress
RC	Reinforced Concrete
UTM	Universal Testing Machine
UW	Unwrapped Specimen
W	CFRP-Wrapped Specimen

List of Symbols

b	Width of Slab	mm
d	Effective Depth	mm
E	Total Energy Absorption	kN-mm
E_1	Energy Absorbed up to First Cracking	kN-mm
E_2	Post-Cracking Energy Absorption	kN-mm
f_r	Flexural Strength	MPa
FTI	Fracture Toughness Index (E/E_1)	—
L	Span Length	mm
P	Applied Load	kN
P_u	Ultimate Load	kN
V_f	Steel Fiber Volume Fraction	%
Δ	Change in Value	—
δ	Mid-span Deflection	mm
δ_{cr}	Deflection at First Cracking	mm
ε	Strain	—
ε_{cr}	Strain at First Cracking	—
ε_u	Ultimate Strain	—
ρ_f	Fiber Reinforcement Ratio	%
σ	Flexural Stress	MPa
σ_{cr}	Cracking Stress	MPa
σ_u	Ultimate Flexural Stress	MPa

Chapter 1

Introduction

1.1 Prologue

Bendable composites, particularly Engineered Cementitious Composites (ECC), have evolved into state-of-the-art materials that exhibit a variety of strain-hardening and microcracking properties under tensile loads. Compared to conventional Portland Cement Concrete (PCC), which degrades brittly, ECC has greater ductility, crack width management, and energy absorption capacity. However, even high-performance composites like ECC can be damaged by stress, exhaustion, or environmental exposure. Restoring the strength and serviceability of such damaged composites is therefore a major undertaking. Carbon fiber reinforced polymer (CFRP) sheets are now often utilized in structural strengthening applications because they are lightweight, resistant to corrosion, and easy to install. When externally attached to damaged structural components, CFRP sheets provide additional confinement and tensile resistance, enhancing flexural strength, stiffness, and durability. The interaction between the composite substrate and CFRP reinforcement determines the strengthening system's effectiveness. The strength recovery behavior of damaged bendable composite slabs reinforced with externally bonded CFRP sheets is investigated in this work. The study evaluates mechanical performance measures such load carrying capability, stiffness enhancement, fracture control, and ductility improvement. By better understanding the structural

behavior of damaged bendable composite slabs before and after CFRP strengthening, this work seeks to contribute to the development of dependable rehabilitation approaches for sustainable infrastructure. The findings of this study should provide scientific understanding and practical suggestions for using CFRP-based strengthening techniques in damaged composite structures in order to enhance durability, safety, and long-term structural resilience.

1.2 Research Motivation and Problem Statement

Damage to structural slabs can occur because of excessive flexural loading, repeated loading, accidental actions, deterioration, or other service-related conditions. When cracking becomes significant, the stiffness, load-carrying capacity, deformation behaviour, and post-cracking performance of the slab may be reduced. Bendable composite (BC) materials provide improved deformation capacity and crack-control characteristics compared with conventional cementitious materials; however, these characteristics do not eliminate the possibility of structural damage. Therefore, an effective rehabilitation technique is required to restore a measurable portion of the lost structural capacity while maintaining the beneficial deformation and post-cracking characteristics of the composite.

Externally bonded Carbon Fibre Reinforced Polymer (CFRP) sheets provide a practical strengthening option because of their high tensile strength, low self-weight, corrosion resistance, and ability to be bonded to the tension face of flexural members. CFRP strengthening can provide additional tensile resistance and can modify the load–deformation and post-cracking response of a damaged member. The motivation for the present study is therefore to investigate whether CFRP sheets can effectively restore the flexural performance of damaged BC slabs and to quantify the resulting strength regain

The research problem addressed in this study is the limited experimental understanding of the extent to which the flexural capacity and post-cracking performance of deliberately damaged bendable composite (BC) slabs can be recovered

through externally bonded Carbon Fibre Reinforced Polymer (CFRP) strengthening. Although CFRP has been widely used for strengthening conventional concrete members, the strength regain of damaged BC slabs after CFRP rehabilitation requires specific experimental evaluation. In particular, it is necessary to determine the change in peak load, flexural stress, deformation, energy absorption, Flexural Toughness Index (FTI), and failure behaviour before and after strengthening.

Accordingly, this research experimentally investigates damaged BC slabs containing 1.0%, 1.5%, and 2.0% internal steel reinforcement ratios. The specimens are initially subjected to flexural loading to establish their original structural response and induce a controlled damaged condition. Following the initial loading, the damaged specimens are strengthened using externally bonded CFRP sheets and subsequently retested under the same loading configuration.

The primary research objective is to quantify the strength regained through CFRP strengthening and to evaluate the influence of the internal steel reinforcement ratio on the structural response of the strengthened BC slabs. The experimental results are compared in terms of load-carrying capacity, deformation behaviour, and flexural performance before and after CFRP strengthening. The findings are intended to provide practical insight into the effectiveness of CFRP sheets for the rehabilitation of damaged BC slabs and to support their application in structural repair and strengthening.

1.2.1 Research Questions

- i. What improvement can be achieved within the elastic range of BC slabs through CFRP wrapping?
- ii. How can the failure mechanism of BC slabs be improved through CFRP wrapping?
- iii. How much strength can be regained in damaged BC slabs using CFRP wrapping?
- iv. Can the Peak Load of CFRP-Wrapped Bendable Composite Slabs Be Accurately Predicted by an Empirical Equation?

- v. What will be the efficiency of wrapping for determining strength of slabs?
- vi. How can CFRP wrapping be practically implemented for the rehabilitation of damaged BC slabs?

1.3 Overall Goal of the Research Program and Specific Objective of this MS Thesis

The research program's main goal is to create and verify efficient repair methods utilizing Carbon Fiber Reinforced Polymer (CFRP) sheets in order to prolong the service life of damaged bendable composites, restore their mechanical qualities, and encourage ecologically friendly construction methods. This project aims to increase understanding of material rehabilitation techniques for flexible composites and their application in critical structural elements. The specific goal of this ms research thesis is to examine Structural Rehabilitation of Damaged Bendable Composite Slabs Using Carbon Fibre Reinforced Polymer (CFRP) Sheets.

1.4 Scope of Work and Study Limitations

The purpose of this study is to determine the extent to which externally bonded Carbon Fibre Reinforced Polymer (CFRP) sheets can restore the flexural performance of damaged bendable composite (BC) slabs. The experimental scope covers the fabrication of BC slabs, initial flexural testing, controlled damage, CFRP strengthening, curing, and retesting under the same three-point bending arrangement. The investigation considers three internal steel reinforcement ratios, namely 1.0%, 1.5%, and 2.0%, while the slab geometry, CFRP strengthening configuration, and principal test conditions are kept consistent.

The principal limitations of the study are as follows. First, the investigation is laboratory-based and uses slab specimens of a fixed nominal geometry; therefore, the findings should not be generalized directly to slabs with different dimensions,

boundary conditions, or structural systems. Second, only three internal steel reinforcement ratios (1.0%, 1.5%, and 2.0%) were investigated, so the influence of other reinforcement levels was not established. Third, the study employed one CFRP strengthening configuration and one epoxy-bonding system; the effects of different CFRP layouts, numbers of layers, orientations, anchorage arrangements, or adhesive systems were not experimentally examined.

Fourth, damage was introduced under controlled laboratory flexural loading. The behaviour of naturally damaged slabs with irregular crack patterns, corrosion, impact damage, or other field deterioration mechanisms was not investigated. Fifth, the experimental program focused on monotonic flexural loading and did not include long-term cyclic loading or environmental durability exposure such as sustained moisture, temperature variation, or ultraviolet radiation. Consequently, long-term CFRP durability and field performance require further investigation. Finally, the empirical relationship developed in Chapter 5 is based on the limited experimental dataset used in this study and should be regarded as a preliminary relationship within the investigated range rather than an independently validated design equation.

1.4.1 Rationale Behind Variable Selection

Because of its remarkable mechanical and physical qualities, including its capacity to reinforce and repair damaged flexible composites, CFRP sheets were selected for this investigation. The exceptional combination of high tensile strength, stiffness, and lightweight properties of carbon fiber reinforced polymer (CFRP) sheets allows for the effective repair of damaged composites without sacrificing their flexibility or adding undue weight. The long-term durability of the repairs is supported by CFRP's resistance to environmental deterioration, including moisture, UV exposure, and temperature variations, in comparison with many conventional reinforcement materials. In addition, the externally bonded CFRP system can effectively transfer tensile stresses across critical regions of the damaged slab and contribute to improved load-carrying capacity. Its relatively simple application

process also makes CFRP suitable for strengthening structural elements without extensive modification of the existing geometry. Therefore, the use of CFRP sheets provides a practical strengthening approach for evaluating strength recovery and post-damage flexural performance in BC slabs. Furthermore, CFRP sheets offer a favorable strength-to-weight ratio, which makes them particularly suitable for lightweight strengthening applications. Their use can help control the propagation of existing cracks and improve the overall stiffness of damaged BC slabs. The strengthening system can therefore enhance structural performance while maintaining the functional advantages of the original bendable composite.

1.5 Brief Methodology

The experimental methodology was carried out in a sequential manner. First, the bendable composite (BC) slab specimens were prepared with the selected internal steel reinforcement ratios of 1.0%, 1.5%, and 2.0%. The specimens were then subjected to initial flexural testing to establish their baseline load–deformation behaviour. Controlled flexural damage/pre-cracking was subsequently introduced in the specimens designated for rehabilitation. After unloading and inspection, the damaged slab surfaces were prepared and cleaned for CFRP application.

CFRP sheets were then bonded to the tension face using the adopted epoxy adhesive system and allowed to cure for the specified period. The strengthened specimens were retested under the same flexural loading arrangement used for the initial testing. The responses of the CFRP-strengthened specimens were compared with those of the corresponding damaged unwrapped specimens in terms of peak load, flexural stress, deformation, energy absorption, Flexural Toughness Index (FTI), strength regain, and failure behaviour. Finally, the experimental peak-load results were used to develop and assess a preliminary empirical relationship within the investigated experimental range.

The strengthened specimens were also evaluated to determine the effectiveness of CFRP sheets in restoring the flexural performance lost due to pre-cracking. The

findings were used to establish the influence of CFRP strengthening on the post-damage behaviour of BC slabs and to identify the potential of the technique for practical structural rehabilitation.

1.5.1 Research Novelty or Uniqueness

This study introduces a novel technique for repairing damaged bendable composites using Carbon Fiber Reinforced Polymer (CFRP) sheets in order to restore strength and flexibility—two crucial properties that distinguish these composites from conventional rigid materials. In contrast to previous research that mostly works with rigid composite systems, this work investigates the unique challenges of rehabilitating bendable composites, such as improving repair parameters including fiber orientation, layer thickness, and adhesive characteristics. Combining actual testing with Finite Element Modelling (FEM), which provides a comprehensive understanding of the failure mechanisms and stress distribution in repaired structures, adds even more innovation.

In the realm of composite material engineering, the work addresses a critical need: the repair and reuse of bendable composites, which are increasingly being used in modern construction because of their flexibility and endurance. By demonstrating effective repair methods, our research contributes to extending the lifespan of these materials, reducing material waste, and promoting sustainable construction practices. By providing useful information about how to improve the performance and durability of repaired composites under dynamic and environmental loads, the results further raise the possibility of their wider usage in structural applications. The research's conclusions are significant since bendable composites are used in seismic-resistant buildings, bending architectural elements, and flexible infrastructure. The research directly impacts the infrastructure and building sectors. The established repair procedures can be used to fix damaged parts on-site, saving money on replacements and downtime.

Additionally, by enabling the reuse of damaged composites, the results promote the circular economy by offering a more cost-effective and environmentally friendly

alternative to material replacement and disposal. The optimal repair methods and suggestions proposed in this work can also be used by engineers and practitioners to promote the efficient and sustainable usage of composite materials in real-world applications.

1.5.2 Research Significance and Benefits

Because it directly enhances structural rehabilitation methods for damaged concrete slab structures, the study is significant. In contemporary infrastructure, structural deterioration brought on by aging, exposure to the environment, overloading, and wear and tear is a recurring problem. Since slab elements are the main load-bearing components of buildings, bridges, and industrial floors, they are especially susceptible to stiffness loss and cracking.

Therefore, it is crucial for the building industry to be able to restore mechanical function without completely replacing them. The strength recovery of damaged bendable composite slabs reinforced with Carbon Fibre Strengthened Polymer (CFRP) sheets is experimentally validated in this study. The study provides a thorough grasp of rehabilitation efficacy in controlled laboratory conditions by examining both traditional Portland Cement Concrete (PCC) and Engineered Cementitious Composite (ECC) slabs with different steel reinforcing ratios. Engineers can assess the efficacy of CFRP strengthening in a methodical and quantitative way by measuring ultimate load capacity, cracking behavior, ductility, stiffness improvement, and energy absorption.

The primary contribution of the work is the demonstration that pre-cracked slabs' structural capability can be greatly increased by externally bonded CFRP sheets. This has direct economic implications because rehabilitation is far less expensive than demolition and reconstruction. CFRP's low weight ensures that the structure will encounter minimal extra dead load, preserving overall stability and enhancing performance. Stronger specimens also have better crack management, increasing durability and reducing the need for continuous maintenance. Another important benefit is the research's contribution to sustainable building practices. The study's

preference for restoration over replacement promotes material conservation and the decrease of building waste. Longer-lasting structures cut down on carbon emissions from transportation and the production of new materials. In this sense, the study backs global sustainability goals related to resilient infrastructure and resource management.

This work fills a knowledge gap in academia by evaluating the combined interplay of external CFRP confinement, internal steel reinforcement, and ECC behavior in slab structures. The findings set the stage for next analytical modeling and numerical simulations of reinforced composite slabs. Based on reinforcement ratios and damage levels, the results can be used in practice to assist engineers in selecting the optimal strengthening designs. The research generally benefits technology, the economy, and the environment. It promotes sustainable infrastructure management, extends service life, improves structural safety, and reduces maintenance costs. The rigorous experimental methodology used in this work ensures that its conclusions are reliable, reproducible, and applicable to real-world engineering practice.

1.5.3 Practical Implementation

The practical implications of the research are highly relevant for infrastructure maintenance authorities, rehabilitation contractors, and structural engineers. The results of the experiment demonstrate that externally attached Carbon Fibre Reinforced Polymer (CFRP) sheets can effectively recover and enhance the flexural performance of damaged bendable composite slabs. This provides a technically validated strengthening method that may be applied to real-world structural rehabilitation projects. One of the primary practical outcomes of the study is the confirmation that damaged slab elements do not necessarily require replacement or demolition. Instead, with careful CFRP application, epoxy bonding, and surface preparation, damaged slabs can have their structural capability significantly restored.

This approach reduces construction delays, minimizes disruptions to service operations, and lowers overall restoration costs. These advantages are particularly advantageous for parking structures, commercial buildings, bridges, and industrial floors where structural failure leads to monetary losses. The findings also provide suggestions for selecting appropriate strengthening configurations based on steel reinforcement ratios and substrate type (PCC or ECC). Engineers can utilize the experimental results to estimate strength return percentages, energy absorption improvements, and predicted stiffness increases. This makes it possible to base design decisions for strengthening projects on performance. With an emphasis on surface preparation and curing methods to ensure effective weight transmission, the study also highlights how important it is for the CFRP sheet and the concrete substrate to effectively bind. Additional safety advantages are provided by the enhanced ductility and fracture control seen in CFRP-wrapped slabs in seismically active areas. Under dynamic loading circumstances, increased energy absorption capacity can strengthen structural robustness. Furthermore, because CFRP is lightweight, it may be used to retrofit existing structures without adding undue weight, which is frequently a drawback of conventional steel plate strengthening techniques. The research's technique can also be used as a technical framework to improve manuals and update design standards. Consultants and rehabilitation experts can reliably use CFRP-based systems for slab strengthening applications by integrating experimentally proven data into engineering practice. All things considered, this study's practical consequences go beyond lab testing. The findings offer a workable, effective, and long-lasting strengthening option that may be easily applied in infrastructure restoration projects, resulting in structural systems that are safer and more resilient.

1.5.4 National and Global Impact with Emphasis on SDGs Relevance

The outcomes of this research have both national and global significance, particularly in the context of sustainable infrastructure development. Many developing

and developed nations face serious challenges related to aging infrastructure, increased traffic loads, rapid urbanization, and environmental degradation. Structural rehabilitation has become a national priority in order to maintain safety and serviceability without excessive financial burden. The strengthening methodology investigated in this research provides a cost-effective and technically reliable solution for restoring damaged slab systems, which are widely used in bridges, residential buildings, commercial complexes, and industrial facilities. From a global perspective, this study supports the implementation of Sustainable Development Goals (SDGs). Specifically, it contributes to SDG 9 (Industry, Innovation, and Infrastructure) by promoting innovative composite strengthening techniques for resilient infrastructure.

It aligns with SDG 11 (Sustainable Cities and Communities) by enhancing structural safety and extending the service life of urban infrastructure. Furthermore, by encouraging rehabilitation instead of demolition and reconstruction, this research supports SDG 12 (Responsible Consumption and Production) through reduced material waste and resource conservation. The extended lifespan of strengthened structures also reduces carbon emissions associated with new construction, contributing indirectly to SDG 13 (Climate Action). Thus, the research integrates structural engineering innovation with global sustainability objectives.

1.5.5 Research Challenges

Several technical and experimental challenges were encountered during the course of this study. One major challenge involved achieving controlled pre-cracking of slab specimens to simulate realistic damage conditions without causing premature failure. Ensuring uniform crack distribution and comparable damage levels across specimens required careful load control and monitoring. Another significant challenge was maintaining proper bonding between the CFRP sheets and the concrete substrate. Surface preparation, including cleaning, roughening, and removal of dust particles, was critical to ensure effective adhesion. Any inconsistency in epoxy application or curing conditions could influence the strengthening efficiency

and failure mode. Accurate measurement of load-deflection behavior and energy absorption capacity also required precise instrumentation and calibration of testing equipment. Controlling environmental conditions during curing and testing was essential to minimize variability in experimental results. These challenges highlight the importance of methodological rigor and careful experimental planning in composite strengthening research.

Additionally, achieving consistent specimen geometry and reinforcement placement was important to reduce variations between the tested slabs. Careful handling of the specimens was necessary during transportation, pre-cracking, CFRP application, and subsequent testing to avoid unintended damage. Maintaining the same loading arrangement and testing procedure for both unwrapped and strengthened specimens was also essential for meaningful comparison. Overall, these challenges required careful supervision at each stage of specimen preparation, strengthening, curing, and experimental testing.

1.5.6 Ethical Management Considerations and Risk Management

Throughout the whole study process, ethical integrity was upheld by following the values of truthfulness, openness, precision, and professional accountability. Every attempt was made to guarantee the dependability and repeatability of the results obtained, and all experimental procedures were carried out in compliance with recognized scientific principles. The information gathered during the preparation, testing, and analysis of the specimens was precisely documented and kept unaltered. There was no selective reporting of positive results, and all observations—including unanticipated outcomes, constraints, and failure modes—were objectively recorded. To prevent plagiarism and uphold intellectual property rights, prior research works were properly cited and acknowledged. These steps helped to preserve the research work's legitimacy, authenticity, and academic integrity. From a management standpoint, the experimental program's successful implementation required meticulous planning and coordination.

To guarantee the effective use of laboratory resources and available time, a methodical plan was created for material procurement, specimen casting, curing, damage induction, CFRP application, and flexural testing. To reduce delays and preserve uniformity throughout the experiment, special consideration was paid to the availability of testing apparatus, laboratory space, and building supplies. In order to track the research's development and enable precise data analysis, efficient record-keeping and documentation procedures were also implemented. An essential component of the study was risk management and safety issues. Because the experimental program included flexural testing of ECC slab specimens and reinforced concrete under high loading conditions, the necessary safety measures were put in place to shield staff and equipment from potential risks related to unexpected specimen failure. Throughout the whole testing process, laboratory safety procedures were closely adhered to. Additionally, extra caution was used when handling and applying CFRP sheets and epoxy adhesives, including wearing gloves, safety glasses, and protective clothes. To reduce exposure to potentially hazardous vapors, adequate ventilation was maintained during the mixing and application of epoxy. The research was carried out in a responsible, methodical, and professional manner by putting these ethical, managerial, and safety precautions into practice, guaranteeing both the caliber of the experimental results and the welfare of all participants.

1.5.7 Research Deliverables, Sales and Marketing Potential

The main output of this study is an externally bonded CFRP sheet reinforcing framework for damaged bendable composite slabs. This covers experimental data on energy absorption capacity, stiffness augmentation, ductility improvement, and strength restoration. For structural engineers and consultants, the findings can be converted into useful design suggestions and rehabilitation guidelines. From a business perspective, CFRP-based strengthening systems have a large market potential due to the rising demand for infrastructure restoration around the world.

The results of this study can be used by construction businesses, engineering consulting firms, and material suppliers to promote innovative composite strengthening solutions. Confidence in the use of CFRP systems in both public and private infrastructure projects is increased by their proven effectiveness in repairing damaged slabs. In the construction sector, this opens up possibilities for product creation, technical consulting services, and specialist rehabilitation contracts. All things considered, the research strengthens the connection between laboratory research and real-world engineering application while also making a significant academic contribution and providing observable economic and industrial benefits.

The load response was monitored throughout the test to identify the initiation of cracking and subsequent changes in the flexural behaviour. The recorded peak-load values were used for comparison among specimens with different reinforcement ratios. This approach provided a consistent basis for assessing the changes in load-carrying capacity after CFRP strengthening. The resulting load–deformation curves were also used to examine the overall flexural response of the specimens. The consistency of the testing procedure helped ensure that the observed differences were primarily associated with the strengthening condition. The proposed strengthening approach may also reduce the need for complete replacement of damaged structural elements, thereby supporting more efficient rehabilitation practices. It provides a basis for further development of CFRP-based repair techniques for different types of composite structural members. The experimental findings can assist future researchers in optimizing CFRP configurations, bonding techniques, and strengthening procedures. Overall, the study demonstrates the potential of CFRP strengthening as a practical component of modern structural rehabilitation strategies.

1.6 Thesis Structure

This thesis includes six chapters. That are:

Chapter 1 includes introduction. It covers the background, research motivation, problem statement, and overall and specific aims of this research, scope of work with study limitations, brief methodology, and thesis outline.

Chapter 2 consists literature review. It comprises of background, nature of bendable composite and conventional concrete, use of local material for producing bendable composite, application of bendable composites in structural elements, summary.

Chapter 3. This chapter consists of the experimental scheme, raw ingredients in concrete, mix design casting of specimens, testing, and summary of chapter 3.

Chapter 4 includes the results obtained from tests and their analysis. It describes the background, dynamic properties and mechanical properties of the mixes (PC, bendable composite), miscellaneous properties (water absorption, linear shrinkage, and mass loss), fractured surfaces of tested specimens, and summary of chapter 4.

Chapter 5 explains the guidelines for practical implementation, it has background, optimum combination of fiberglass fiber lengths, application of this research in real life, and summary of chapter 5.

Chapter 6 consists of conclusions and future recommendations. At the end Bibliography is provided.

Chapter 2

Literature Review

2.1 Background

Concrete is one of the most extensively used construction materials because of its availability, relatively low cost, ease of production, and high compressive strength. However, conventional cement-based concrete has comparatively low tensile strength and limited deformation capacity. Under tensile and flexural loading, cracking can develop rapidly and may subsequently result in stiffness degradation, loss of serviceability, and brittle failure if the cracking is not adequately controlled [1-2].

To overcome these limitations, researchers have developed high-performance fibre-reinforced cementitious composites with improved tensile behaviour, crack control, ductility, and energy absorption. Engineered Cementitious Composite (ECC) is one important class of strain-hardening cementitious composites that has been extensively investigated because of its ability to develop multiple closely spaced cracks rather than a single dominant crack [1-5-21]. The micro mechanical interaction between the cementitious matrix and dispersed fibres allows these composites to sustain deformation beyond first cracking and provides a more gradual failure response than conventional concrete [6-7].

The term bendable composite (BC) is used in this thesis as the broader terminology for the investigated cementitious composite system. Although the literature frequently discusses ECC as a form of bendable concrete, the two terms are not

treated as automatically identical in this research. ECC is discussed where the cited literature specifically concerns Engineered Cementitious Composite, whereas BC refers to the material system investigated in the present experimental program.

The improved deformation and crack-control characteristics of bendable cementitious composites make them attractive for structural and rehabilitation applications. Nevertheless, improved ductility does not make these materials immune to damage. Excessive flexural loading, repeated loading, accidental actions, and deterioration can produce cracks and reduce the structural capacity of a member[24-25]. Therefore, rehabilitation techniques capable of restoring the load-carrying capacity of damaged composite members remain important.

Externally bonded Carbon Fibre Reinforced Polymer (CFRP) systems have become an established strengthening technique for concrete and cement-based structural members. CFRP sheets possess high tensile strength, high stiffness-to-weight ratio, low density, and resistance to corrosion. When appropriately bonded to the tension face of a flexural member, they can provide additional tensile resistance and modify the post-cracking response of the strengthened member [3-4-31-33-34].

The literature reviewed in this chapter is therefore focused on the aspects directly related to the present research: the behaviour of bendable cementitious composites, their cracking and deformation mechanisms, the role of internal steel reinforcement, the strengthening mechanism of CFRP sheets, CFRP bond behaviour, post-cracking performance, energy absorption, toughness, and rehabilitation of damaged structural members. This focus establishes the basis for investigating strength regain in damaged bendable composite slabs strengthened with externally bonded CFRP sheets. The rationale for the literature review is established from four directly related areas. First, studies on bendable and Engineered Cementitious Composite materials provide the background for deformation capacity, controlled cracking, ductility, post-cracking behaviour, and energy absorption. Second, research concerning damaged cementitious and reinforced structural members establishes the need for effective rehabilitation when cracking and damage reduce structural performance. Third, previous investigations of externally bonded Carbon Fibre Reinforced Polymer (CFRP) systems establish the

importance of CFRP tensile resistance, bond behaviour, surface preparation, and flexural strengthening. Fourth, studies combining strain-hardening cementitious composites with fibre-reinforced polymer systems provide a basis for considering hybrid rehabilitation approaches.

Although these research areas provide substantial technical knowledge, comparatively limited experimental evidence is available concerning the quantitative strength regain of deliberately damaged bendable composite slabs after CFRP strengthening. In particular, the influence of the internal steel reinforcement ratio on regained peak load, flexural stress, deformation, energy absorption, Flexural Toughness Index, and failure behaviour requires further experimental assessment. Therefore, the literature reviewed in this chapter is used not only to establish the general background of BC and CFRP systems but also to identify the specific research gap addressed by the present experimental investigation.

Accordingly, the subsequent sections are organized around bendable-composite behaviour, cracking and post-cracking mechanisms, internal steel reinforcement, CFRP strengthening and bond behaviour, energy absorption and toughness, failure mechanisms, and rehabilitation of damaged structural members. This organization provides a direct connection between the reviewed literature, the identified research gap, and the experimental program undertaken in this thesis.

2.2 Need for New Composite Unique Structures

Conventional concrete provides adequate compressive resistance for many structural applications but has inherent limitations under tensile and flexural loading. Once tensile cracking develops, the capacity of an unreinforced cementitious matrix to sustain additional deformation is limited. Consequently, the development of materials capable of controlling cracks while maintaining load-carrying capacity after cracking has become an important research area [1-2]. Strain-hardening cementitious composites were developed to address this limitation. These composites are designed so that cracking of the matrix does not immediately result in loss of load-carrying capability. Instead, reinforcement across the cracks allows the

material to continue carrying load while additional cracks develop. This behaviour provides higher deformation capacity and improved energy absorption compared with conventional concrete [5-6-21].

The structural benefit of such composites is particularly relevant for members subjected to flexural actions. Controlled cracking can reduce the concentration of deformation at a single crack and provide a more distributed damage pattern. The resulting behaviour can improve serviceability and delay the development of a critical failure mechanism [15-16-17].

However, a bendable composite structural member can still suffer significant damage when the applied demand exceeds its capacity. Once a slab has experienced substantial cracking, its stiffness and load-carrying mechanism may change. Consequently, the ability to repair and strengthen a damaged member is an important consideration for extending its service life. For this reason, the present research considers a two-stage structural system. The first stage consists of the bendable composite slab with internal steel reinforcement, while the second stage involves externally bonded CFRP sheets applied after controlled flexural damage. The literature on CFRP strengthening provides evidence that externally bonded fibre-reinforced polymer systems can improve the flexural performance of damaged or deficient concrete members [3-4-31-32].

The combination of a ductile cementitious substrate and an external high-strength CFRP reinforcement therefore provides a rational basis for investigating whether lost flexural capacity can be recovered after controlled damage. The relevant mechanisms are discussed in the following subsections.

2.2.1 Micro-Mechanics and Strain Hardening Behaviour

The enhanced tensile behaviour of strain-hardening cementitious composites is fundamentally associated with the interaction between the cementitious matrix and the reinforcing fibres. Micromechanical design considers matrix cracking, fibre bridging, fibre pull-out, and the transfer of stress across developing cracks [5-6-7]. In a conventional cementitious matrix, once a crack becomes critical, stress

becomes concentrated around the crack and the material may experience rapid localization. In a strain-hardening composite, reinforcement crossing the crack provides a mechanism for transferring tensile stress from one side of the crack to the other. Continued loading can therefore produce additional cracks while the overall member continues to carry load [17-21].

The fibre-bridging mechanism is particularly important because the bridging reinforcement provides resistance against crack opening. The effectiveness of this mechanism depends on several factors, including fibre properties, fibre-matrix interaction, matrix strength, fibre distribution, and the stress-transfer characteristics at the crack interface [5-7-17].

Li [1] described ECC as a material system designed around micromechanical principles to obtain high tensile ductility and controlled multiple cracking. The strain-hardening response occurs when the bridging capacity available across developing cracks is sufficient to sustain additional loading after matrix cracking[1-21].

This behaviour distinguishes strain-hardening cementitious composites from conventional concrete. Instead of concentrating deformation at one dominant crack, deformation can be distributed among multiple cracks. Such behaviour is beneficial where structural members are required to tolerate significant deformation before failure.

For the present research, this concept is important because the initial slab is deliberately subjected to flexural loading before CFRP strengthening. The ability of the bendable composite slab to develop controlled cracking provides a suitable basis for examining the subsequent effect of CFRP rehabilitation. It is important to distinguish the micromechanical fibre behaviour reported in ECC literature from the steel reinforcement used in the present slab specimens. The present experimental investigation varies the ratio of internal steel reinforcement at 1.0%, 1.5%, and 2.0%. These percentages represent the steel reinforcement used in the slab system and are not treated as steel-fibre volume fractions. The resulting differences in reinforcement ratio provide a basis for assessing changes in load-carrying capacity and deformation behaviour after strengthening. This approach

also enables a direct comparison of the effectiveness of CFRP rehabilitation for slabs with different levels of internal steel reinforcement.

2.2.2 Multiple Cracking and Crack Width Control

One of the principal advantages associated with bendable cementitious composites is their ability to distribute deformation through multiple cracks. Instead of allowing one crack to become dominant at an early stage, the development of multiple cracks can distribute tensile deformation over a larger region [15-17]. Crack-width control is important because wide cracks can adversely affect structural serviceability and may provide pathways for moisture and aggressive agents. Research on ECC has demonstrated that controlled microcracking can contribute to improved durability by limiting crack widths and reducing the transport of harmful substances through the cracked material [9-10-13-15].

The development of multiple cracks is related to the balance between matrix cracking resistance and the bridging capacity of the reinforcement crossing the cracks. Once the conditions for continued cracking are satisfied, new cracks can form while existing cracks remain relatively controlled [17]. Under flexural loading, this mechanism can result in a distributed cracking pattern through the tensile region of a slab. The resulting response is generally more gradual than the abrupt cracking associated with ordinary cement concrete. Such behaviour is particularly useful when deformation and energy absorption are important design considerations.

2.2.3 Applications of Bendable Concrete in Unique Structural Systems

The improved tensile ductility, crack-width control, and durability of strain-hardening cementitious composites have resulted in their investigation for a variety of structural applications. Previous research has considered ECC in bridge deck link slabs, repair layers, structural components, seismic applications, and other systems where deformation and crack control are important [14-16-25-53]. The application

of bendable composites is particularly relevant to structural members in which cracking and deformation control influence serviceability. Bridge deck link slabs, for example, have been investigated because the material can accommodate deformation while controlling crack development [14]. ECC has also been investigated for strengthening and rehabilitation of existing reinforced concrete structures [24-54].

Recent reviews have highlighted the potential of engineered cementitious composites for resilient infrastructure because of their combination of tensile strain capacity, crack control, durability, and structural compatibility [25-27-51-53]. Although these applications demonstrate the potential of bendable composites, they do not directly answer the question addressed by this thesis: how much flexural capacity can be recovered when an already damaged bendable composite slab is strengthened using externally bonded CFRP sheets?

Therefore, the present literature review places greater emphasis on the damage and rehabilitation stage rather than discussing applications that are not directly related to the research objectives.

2.3 CFRP Strengthening of Structural Elements

Fibre-reinforced polymer composites have become widely used in structural rehabilitation because they can provide additional tensile or confinement resistance without substantially increasing the self-weight of the strengthened member.

Among different FRP systems, CFRP is particularly attractive because carbon fibres possess high tensile strength and stiffness and are not susceptible to conventional steel corrosion [3-4-33-34]. CFRP strengthening systems generally consist of high-strength carbon fibres embedded in or combined with a polymeric resin system. For externally bonded applications, the CFRP sheet is attached to the prepared surface of the existing structural member using an adhesive, commonly an epoxy-based system. The effectiveness of the strengthening system therefore depends not only on the mechanical properties of the CFRP but also on the quality of the interface between the CFRP and the substrate [4-31-33]. For flexural

strengthening, CFRP sheets are normally placed on the tension face of the structural member. After cracking, tensile stresses that would otherwise be resisted primarily by the internal reinforcement and cementitious matrix can be transferred partly to the externally bonded CFRP. This additional tensile resistance can increase flexural capacity and delay further crack development[3-4-32]. The strengthening mechanism is therefore based on composite action between the existing structural member, internal reinforcement, adhesive layer, and CFRP sheet. Adequate surface preparation and bond development are essential because premature debonding can prevent the CFRP from reaching its full tensile capacity[4-31].

2.3.1 Damage in Bendable Composites and Need for External Strengthening

The improved ductility of bendable composites does not mean that structural damage cannot occur. Excessive flexural loading can produce cracking and eventually reduce the stiffness and load-carrying capacity of a structural member. Environmental actions, repeated loading, accidental loading, and other forms of deterioration can also affect structural performance [24-25]. Once significant damage has occurred, the original material alone may not be capable of restoring the required structural capacity. Conventional repair methods may involve removal and replacement of damaged material, section enlargement, or addition of conventional strengthening components. Such methods can increase construction time, dead load, and disruption to the existing structure.

Externally bonded CFRP provides an alternative because it can be installed directly onto the existing structural surface with relatively little increase in member dimensions and self-weight [3-4-34].

For a damaged bendable composite slab, CFRP can provide an additional tensile load path after cracking. This is particularly relevant to the strength-regain concept investigated in this thesis. Rather than replacing the damaged slab, the CFRP system is used to supplement the remaining structural capacity and determine the extent to which the original flexural performance can be recovered. Recent

research has also begun to examine CFRP and other FRP systems in combination with engineered cementitious composites. For example, research on predamaged ECC and CFRP-confined systems demonstrates increasing interest in the interaction between damaged cementitious composites and external fibre-reinforced strengthening systems [61].

2.3.2 Effect of CFRP on Load Carrying Capacity and Stiffness

The effectiveness of CFRP strengthening in flexural members has been demonstrated through numerous experimental investigations. CFRP sheets can increase the ultimate load capacity of reinforced concrete members and can modify their load–deflection response by providing additional tensile resistance[3-32-33].The magnitude of strengthening depends on several factors, including the amount and orientation of CFRP, bond length, substrate condition, internal reinforcement, anchorage, and loading configuration[3-4-31-34].

When bonded to the tension face, the CFRP sheet begins to participate significantly after tensile cracking develops. The additional tensile resistance can reduce the rate of crack widening and increase the load that can be sustained before failure. The resulting load–deflection response may therefore show improved post-cracking stiffness and increased ultimate load.The bond between CFRP and the cementitious substrate is particularly important. The applied tensile force must be transferred from the substrate to the CFRP through the adhesive interface. Poor surface preparation, insufficient bond length, air voids, or inadequate curing can lead to premature debonding and reduce strengthening efficiency [4-31].

CFRP strengthening can also alter the failure mechanism. Instead of failure being governed solely by cracking of the cementitious substrate, the strengthened system may experience combinations of concrete cracking, adhesive failure, interfacial debonding, or CFRP rupture. Therefore, examination of the failure mechanism is necessary when evaluating the effectiveness of a strengthening system.These observations are directly relevant to the present study because the performance

of the repaired slabs is evaluated not only by ultimate load but also through load–deflection response, deformation, energy absorption, flexural toughness, and observed failure behaviour. For hydrophilic fiber systems, like polyvinyl alcohol

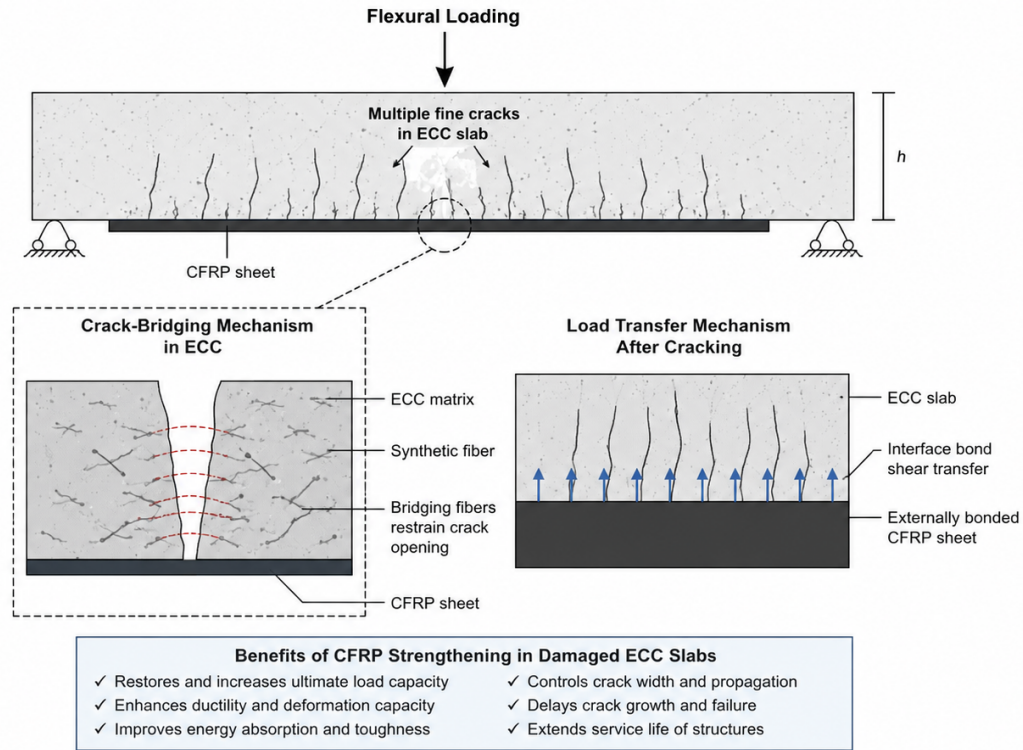


FIGURE 2.1: Crack opening mechanism in an ECC slab under flexural loading
Source: Adapted from Li, V. C. (2018). Engineered Cementitious Composites (ECC): Material, Structural, and Durability Performance (2nd ed.). Springer Nature.

(PVA), strong chemical bonding between the fiber and the surrounding matrix is often expected, and both chemical adherence and friction control the strength of the fiber/matrix interface contact.

The link between the opening of fractures in a concrete or composite substrate and the fiber bridging strength of a CFRP sheet is depicted in Figure 2.1. The CFRP sheet that is externally bonded starts to prevent crack opening through a fiber-bridging mechanism when a crack starts in the tension zone of a structural member. Through this technique, tensile forces that would otherwise cause the cracks to spread are carried by carbon fibers that bridge across the crack sides. Strong adhesion between the CFRP sheet and the substrate allows the CFRP fibers

TABLE 2.1: Composite Properties of ECC and CFRP Sheets

Property	ECC	CFRP Sheet
Density	2200–2400 kg/m ³	1.6–1.8 g/cm ³
Compressive Strength	30–50 MPa	–
Tensile Strength	4–8 MPa	3800–4200 MPa
Elastic Modulus	18–25 GPa	230–250 GPa
Ultimate Strain	2.0–3.0%	1.5–1.7%
Fiber Type	Polypropylene/PVA Fibers	High-Strength Carbon Fiber
Fiber Orientation	Random Distribution	Unidirectional
Sheet Thickness	–	0.111–0.167 mm
Bonding Method	–	Externally Bonded Using Epoxy Resin
Corrosion Resistance	Moderate	Excellent (Non-Metallic)

Source: Adapted from Li (2019) and ACI 440.2R-17.

to efficiently transfer stresses over small crack gaps. Because of the mobilization of fiber tensile strength, the CFRP sheet's bridging stress grows as the crack opening does. Controlled fracture growth and effective stress transfer are characteristics of this stage. The fiber's bridging strength peaks as it passes a crucial crack opening. Depending on the bonding quality and material characteristics, a further increase in crack width may cause a progressive decrease in bridging stress as a result of fiber debonding, resin cracking, or fiber rupture. This response emphasizes how crucial adequate anchoring length and surface preparation are to ensuring efficient load transmission between the CFRP sheet and the substrate. In order to improve post-cracking stiffness, regulate crack widths, and restore the load-carrying capacity of damaged structural parts, CFRP's fiber bridging mechanism is essential. This behavior is especially advantageous for ECC and reinforced concrete slab rehabilitation applications, where preventing cracks from spreading is crucial for long-term durability and serviceability. Selection of CFRP sheets Because of its exceptional mechanical properties, durability, and appropriateness for use with flexible composites, CFRP sheets were selected for this investigation. CFRP sheets are lightweight, stiff, and have a high tensile strength because of the high-strength carbon fibers that are integrated into a polymer matrix, typically epoxy resin. These characteristics make CFRP sheets particularly effective at restoring

the mechanical properties of damaged materials without noticeably altering their flexibility or weight.

The fiber-bridging behavior shown in Figure 2.1 is directly connected to the characteristics of CFRP sheets listed in Table 2.1. The fibers of CFRP can successfully fill up cracks that form in the tension zone of concrete or ECC parts because of their high tensile strength and elastic modulus. The unidirectional carbon fibers transfer tensile loads across the crack faces as the crack opens up, preventing additional crack widening. In reinforced members, this fiber-bridging action improves post-cracking stiffness and slows the course of damage. Additionally, the CFRP sheets' superior bonding properties, which are made possible by epoxy adhesives, guarantee effective stress transfer between the CFRP and the substrate. As seen in Figure 2.1, this robust link enables the CFRP fibers to fully utilize their tensile potential, increasing the bridging strength to a maximum value. Debonding or fiber rupture may cause failure after this point, underscoring the significance of proper anchorage length and surface preparation. Overall, CFRP sheets' capacity to limit crack opening and rebuild strength in damaged ECC and reinforced concrete slabs can be explained by the mechanical and durability characteristics listed in Table 2.1.

Table 2.2 presents the principal mechanical and physical attributes of Carbon Fibre Reinforced Polymer (CFRP) sheets used for structural strengthening applications. The properties listed in the table demonstrate why CFRP has become one of the most effective externally bonded reinforcement materials for rehabilitating damaged concrete and composite structures. The high tensile strength of CFRP, ranging from 3800 to 4200 MPa, enables it to carry substantial tensile forces that develop in the tension zone of flexural members after concrete cracking. This tensile capacity is significantly greater than that of conventional structural steel, allowing CFRP sheets to effectively restore and enhance the flexural strength of damaged slabs. The elastic modulus of 230–250 GPa indicates that CFRP possesses high stiffness, enabling efficient stress transfer from the concrete substrate to the reinforcement through the epoxy adhesive. Although the ultimate tensile strain

of CFRP is relatively small (1.5–1.7%), its high tensile strength allows the material to perform efficiently until failure. The sheet thickness of 0.111–0.167 mm provides additional reinforcement without significantly increasing the dimensions or self-weight of the strengthened structural member. The use of a two-part epoxy adhesive ensures adequate bonding between the CFRP sheet and the concrete surface, while the resin tensile strength of 60–75 MPa and glass transition temperature of 60–80°C provide sufficient mechanical performance under normal service conditions. Furthermore, the excellent corrosion resistance, negligible water absorption, and wide operating temperature range contribute to the long-term durability of CFRP strengthening systems, particularly in aggressive environmental conditions where conventional steel reinforcement may deteriorate.

Overall, the properties summarized in Table 2.2 highlight the superior mechanical performance, lightweight nature, and environmental durability of CFRP sheets. These characteristics make CFRP an ideal strengthening material for the rehabilitation of damaged bendable composite slabs, where improved load-carrying capacity, enhanced crack control, and extended service life are required. The combination of high tensile strength, excellent bond characteristics, and resistance to corrosion enables CFRP sheets to provide an efficient and sustainable solution for modern structural rehabilitation. The enhancements in structural performance attained by applying Carbon Fibre Reinforced Polymer (CFRP) sheets on concrete or ECC examples are compiled in Table 2.3. Comparing CFRP-strengthened specimens to unstrengthened ones, the results show a considerable increase in flexural strength and ultimate load-carrying capacity. The main reason for this improvement is CFRP sheets' high tensile strength and stiffness, which enable them to successfully withstand tensile pressures in the tension zone following substrate material cracking.

The effectiveness of CFRP in limiting crack propagation is demonstrated by the decrease in crack width seen in specimens reinforced with CFRP. CFRP sheets increase post-cracking stiffness and slow fracture widening by bridging cracks and distributing tensile stresses across crack faces. Furthermore, the rise in the ductility index and final deflection indicates that CFRP strengthening improves energy

TABLE 2.2: Attributes of CFRP Sheets

Property	Symbol/Unit	Typical Value or Description
Fiber Type	–	High-Strength Carbon Fiber
Fiber Orientation	–	Unidirectional
Density	ρ (g/cm ³)	1.6–1.8
Tensile Strength	f_t (MPa)	3800–4200
Elastic Modulus	E (GPa)	230–250
Ultimate Strain	ε_u (%)	1.5–1.7
Sheet Thickness	t (mm)	0.111–0.167
Resin Type	–	Two-Part Epoxy Adhesive
Tensile Strength of Resin	f_r (MPa)	60–75
Glass Transition Temperature	T_g (°C)	60–80
Bonding Method	–	Externally Bonded with Epoxy Resin
Corrosion Resistance	–	Excellent (Non-Metallic)
Water Absorption	–	< 0.5%
Operating Temperature Range	–	–20°C to +80°C

Source: Adapted from Li (2019) and ACI 440.2R-17.

absorption, deformation capacity, and strength, all of which contribute to improved structural performance. Additionally, Table 2.3 indicates that CFRP-strengthened specimens generally achieve a high load recovery ratio, typically ranging from 80% to 90%, along with improved durability. Unlike the abrupt cracking commonly observed in unstrengthened concrete elements, CFRP-strengthened specimens generally exhibit failure mechanisms such as CFRP debonding and fibre rupture, indicating a modification in the overall failure process. These findings demonstrate the potential of CFRP sheets as an effective external strengthening material for repairing damaged structural components and enhancing their structural performance and serviceability. The CFRP sheets also provide additional tensile resistance across cracked regions, helping to control crack propagation and maintain load-carrying capacity after damage. The effectiveness of strengthening depends on

TABLE 2.3: Summary of Previous Studies on CFRP Strengthening

Study	Specimen Type	Strength Increase (%)	Key Observation
Teng et al. (2002)	RC Beams	20–40	Significant improvement in flexural capacity.
Buyukozturk (2004)	RC Members	15–35	Improved crack control and bond performance.
Seracino (2007)	Slab Elements	25–45	Enhanced stiffness and delayed structural failure.
Wang et al. (2020)	RC Slabs	30–50	Increased load-carrying capacity under flexure.
Hassan et al. (2022)	Pre-cracked Beams	35–60	Effective restoration of strength after damage.
Saeed et al. (2023)	Slab Specimens	40–65	Improved energy absorption and ductility.
Alam (2024)	Strengthened RC Systems	30–55	Enhanced ductility and long-term durability.

Source: Compiled from Teng et al. (2002), Buyukozturk (2004), Seracino (2007), Wang et al. (2020), Hassan et al. (2022), Saeed et al. (2023), and Alam (2024).

proper surface preparation, adequate epoxy bonding, and sufficient curing of the CFRP system. Properly bonded CFRP can improve the stiffness and deformation capacity of damaged members under subsequent loading. Therefore, CFRP strengthening can contribute to the restoration of structural performance while reducing the need for complete replacement of damaged components.

2.3.3 CFRP Used in Different Studies

CFRP strengthening has been extensively investigated for reinforced concrete beams, slabs, columns, and other structural members. Chen and Teng [31] investigated FRP strengthening of reinforced concrete members and demonstrated the importance of bond behaviour in the development of strengthening capacity. Esfahani et al. [32] investigated the flexural behaviour of reinforced concrete beams strengthened with CFRP sheets and reported improvements in flexural performance. Nanni [33] and Hollaway and Teng [34] have documented the

broader application of FRP systems for structural strengthening and rehabilitation. These studies establish the technical basis for using externally bonded CFRP as a strengthening system. More recent research has expanded the use of ECC and FRP systems. Studies and reviews have investigated ECC strengthening, FRP-reinforced cementitious composites, and the behaviour of damaged composite systems [24-35-54-61]. These developments demonstrate that the interaction between advanced cementitious materials and external fibre-reinforced polymer systems is becoming an increasingly relevant area of structural rehabilitation research.

However, most of the established CFRP literature concerns conventional reinforced concrete members or the strengthening of undamaged or deficient structural members. Comparatively less attention has been given to controlled damage followed by CFRP strengthening of bendable composite slabs, particularly when the principal objective is to quantify the regain in flexural capacity. In particular, limited experimental evidence is available on the behaviour of previously damaged BC slabs after the application of externally bonded CFRP sheets. The influence of different internal steel reinforcement ratios on the extent of strength recovery also requires further investigation. A systematic comparison between the original, damaged, and CFRP-strengthened responses can provide a clearer understanding of the rehabilitation mechanism. Therefore, this study addresses this gap by experimentally evaluating the flexural performance and strength regain of damaged BC slabs strengthened with CFRP sheets.

The study further considers changes in deformation capacity and energy absorption to provide a broader assessment of the post-rehabilitation response. The experimental comparison also helps identify how variations in steel reinforcement content affect the effectiveness of CFRP strengthening. In addition, the observed failure behaviour is examined to understand the response of the strengthened slabs under flexural loading.

2.4 Application of CFRP sheets in Structural Elements

CFRP strengthening is used in a variety of structural rehabilitation applications. The basic strengthening concept remains the same: the CFRP system is bonded to the existing structural member so that the carbon fibres provide additional resistance in the direction of the principal stress. The application selected for a particular member depends on the dominant structural demand. For flexural members such as beams and slabs, CFRP is commonly placed along the tension face. For columns, wrapping can be used to provide confinement. In repair applications, the CFRP configuration must also account for the location and extent of existing damage [3-4-34]. Although CFRP has been used in buildings, bridges, and other infrastructure, the present study focuses specifically on the flexural rehabilitation of damaged bendable composite slabs. The following applications are therefore included only to establish the broader relevance of CFRP rehabilitation. CFRP systems are widely used in building structures to enhance the load-carrying capacity of beams, slabs, columns, and other structural members. In bridge decks, CFRP sheets can help address cracking and deterioration associated with repeated traffic and dynamic loading, thereby contributing to the extension of service life. CFRP reinforcement can also improve the resistance of walls, chimneys, and other structural elements to lateral loads such as wind and seismic actions. CFRP sheets are further used for repairing damaged or deteriorated structural components, allowing their strength and functionality to be restored without complete replacement. Because of their adaptability, CFRP sheets can be applied to curved or irregular surfaces, increasing their suitability for architectural and heritage restoration. These applications demonstrate the versatility of CFRP as a strengthening and rehabilitation material in modern structural engineering. In the context of the present study, this broader application background supports the investigation of CFRP as a rehabilitation technique for damaged BC slabs. The experimental assessment provides specific evidence regarding its effectiveness under flexural loading after controlled damage. The findings may also contribute

TABLE 2.4: Comparison of CFRP and Steel Strengthening Systems

Parameter	CFRP Sheets	Steel Plates
Density	1.6–1.8 g/cm ³	7.85 g/cm ³
Tensile Strength	3800–4200 MPa	400–600 MPa
Elastic Modulus	230–250 GPa	200 GPa
Corrosion Resistance	Excellent (Non-Metallic)	Prone to Corrosion
Weight Addition	Very Low	High
Ease of Installation	Easy and Flexible	Requires Heavy Equipment
Maintenance Requirement	Minimal	Regular Maintenance Required
Durability	High Durability	Moderate Durability
Cost	Higher Material Cost	Lower Material Cost
Long-Term Performance	Stable Under Environmental Exposure	Susceptible to Rust and Moisture

Source: Compiled from ACI 440.2R-17, ACI 318-19, and the manufacturer's technical datasheets.

to the development of practical strengthening approaches for similar cementitious composite slab systems.

2.4.1 Building Infrastructure

CFRP systems have been applied to reinforced concrete beams, slabs, columns, walls, and other structural components in buildings. In flexural applications, CFRP sheets can be bonded to the tension face of beams and slabs to increase their flexural resistance. In columns, wrapping configurations can provide confinement and improve deformation capacity [3-4-34]. For slab systems, CFRP strengthening can be useful where an existing member has experienced cracking, deterioration, or an increase in imposed loading. Since the CFRP layer is thin and lightweight,

strengthening can generally be achieved without the substantial geometric changes associated with conventional section enlargement. This characteristic is particularly relevant to rehabilitation because maintaining the existing dimensions and reducing construction disruption can be important practical considerations. For the present study, the building-related application most relevant is the rehabilitation of flexure-damaged slab members. The experimental work therefore concentrates on the tension-face application of CFRP rather than column confinement or shear strengthening. This approach allows the strengthening material to work directly in the region subjected to tensile stresses during flexural loading. It also provides an efficient means of improving the structural response while preserving the original configuration of the slab. Additionally, the technique can be applied with relatively limited changes to the existing structural system. The externally bonded CFRP layer can provide additional tensile resistance and help control the development of flexural cracks. This may improve the serviceability and load-carrying performance of damaged slabs after rehabilitation. Therefore, the selected strengthening configuration is consistent with the objective of evaluating flexural strength recovery in damaged BC slab specimens.

2.4.2 Transportation Infrastructure

CFRP has also been investigated for the rehabilitation of transportation infrastructure, particularly bridge decks, beams, girders, and other components exposed to repeated traffic loading and environmental deterioration [14-34]. Bridge and transportation structures can experience progressive deterioration due to repeated loading, cracking, corrosion of conventional reinforcement, and environmental exposure. CFRP strengthening can provide additional tensile capacity while minimizing additional structural weight.

Its externally bonded application can also reduce the need for extensive modification of existing structural components during rehabilitation. The effectiveness of CFRP systems depends on adequate surface preparation, proper bonding, and appropriate detailing at critical regions. These factors are particularly important

when strengthening previously damaged structural members, where the existing substrate may contain cracks or localized deterioration.

The relevance of such applications to the present research is primarily associated with rehabilitation. A damaged structural member does not necessarily need to be completely replaced if sufficient residual capacity remains and an effective strengthening system can restore the required performance. This rehabilitation approach can reduce material consumption, construction time, and disruption compared with complete replacement. It also provides an opportunity to evaluate the extent to which the original structural capacity can be recovered after damage. Therefore, the principles of CFRP-based rehabilitation provide a useful basis for investigating strength regain in the damaged BC slabs considered in this study.

However, the present research does not experimentally investigate bridge structures, traffic loading, or environmental durability. Such applications are therefore discussed only to establish the broader structural relevance of CFRP rehabilitation. The discussion provides contextual support for the potential use of CFRP in structural repair beyond the laboratory-scale slab specimens considered in this study. It also helps distinguish the experimentally investigated parameters from applications that require separate field-based assessment.

2.4.3 Other Infrastructure Applications

FRP systems have also been considered for rehabilitation of infrastructure exposed to aggressive environmental conditions. Their corrosion resistance makes them attractive where conventional metallic strengthening may be vulnerable to deterioration[4-33-34]. ECC and other strain-hardening cementitious composites have similarly been investigated for infrastructure rehabilitation because of their crack-control and durability characteristics [9-24-25].

Recent research has increasingly considered combinations of ECC/SHCC with FRP systems, demonstrating the potential for hybrid rehabilitation approaches [35-43-61]. The importance of these developments to the present study is that

both the substrate material and the external strengthening material contribute to structural performance.

The bendable composite provides a comparatively ductile cementitious substrate, while the CFRP provides high tensile resistance after strengthening. This combination can improve the ability of the rehabilitated slab to sustain flexural loads after damage. The interaction between the cementitious substrate and CFRP layer is therefore an important consideration in assessing strength recovery. The effectiveness of this strengthening system depends on adequate stress transfer through the adhesive interface. These considerations provide a basis for evaluating the post-damage flexural response of CFRP-strengthened BC slabs in the present investigation. The combined system may also contribute to improved crack-bridging and stress redistribution within the damaged slab. The presence of the CFRP sheet can provide additional tensile resistance across critical cracked regions. At the same time, the ECC matrix can limit crack widths and distribute deformation over multiple cracks rather than allowing a single crack to dominate the response. This complementary behaviour is particularly relevant when assessing the performance of a slab after pre-cracking and subsequent strengthening. The bond between the CFRP sheet and the substrate is another important factor because inadequate adhesion can limit the transfer of tensile stresses. Proper surface preparation and epoxy application are therefore essential for achieving effective composite action. The strengthening configuration adopted in this study was selected to examine these mechanisms under flexural loading. Particular attention was given to the changes in peak load, deformation, energy absorption, and flexural toughness after CFRP application. The comparison between damaged unwrapped and CFRP-strengthened specimens provides an experimental basis for evaluating the extent of strength recovery. Such evaluation can help clarify the practical potential of externally bonded CFRP sheets for rehabilitation of damaged bendable composite slabs.

2.5 Summary

The literature reviewed in this chapter establishes the technical background required for evaluating CFRP rehabilitation of damaged bendable composite slabs. Conventional concrete has high compressive strength but limited tensile deformation capacity and relatively brittle post-cracking behaviour. Bendable cementitious composites address some of these limitations through controlled cracking, improved tensile deformation, and enhanced energy absorption[1-5-21]. The literature also demonstrates that crack control and distributed deformation are important characteristics for improving the serviceability and durability of cementitious structural systems. Nevertheless, bendable composites can still experience significant structural damage under excessive or repeated loading and may consequently require rehabilitation. CFRP sheets provide an effective external strengthening mechanism because of their high tensile strength, stiffness, low density, and corrosion resistance[4-3-33-34]. When bonded to the tension face of a damaged flexural member, CFRP can provide an additional tensile load path and modify the post-cracking behaviour. The effectiveness of this system depends strongly on bond quality, surface preparation, anchorage, and the interaction between the CFRP and cementitious substrate [4-31].

Previous studies have established CFRP strengthening for conventional reinforced concrete members and have increasingly investigated the combination of FRP systems with ECC/SHCC materials. However, the specific issue of strength regain in controlled-damaged bendable composite slabs strengthened with externally bonded CFRP sheets remains comparatively less investigated. Accordingly, the present research addresses this gap by experimentally investigating damaged bendable composite slabs containing 1.0%, 1.5%, and 2.0% steel reinforcement, followed by CFRP strengthening and retesting. The resulting changes in flexural capacity, deformation, energy absorption, toughness, and failure behaviour provide the basis for assessing the effectiveness of CFRP rehabilitation.

Chapter 3

Experimental Methodology

3.1 Background

The experimental program was designed to investigate the strength regain of damaged bendable composite (BC) slabs strengthened with Carbon Fibre Reinforced Polymer (CFRP) sheets. The investigation consisted of the preparation and casting of the slab specimens, curing, initial flexural testing, controlled introduction of damage, application of CFRP sheets to the damaged specimens, and subsequent retesting. The experimental procedure was planned so that the effect of CFRP strengthening could be evaluated by comparing the structural response of the specimens before and after strengthening. Particular attention was given to the flexural load capacity, deformation behaviour, energy absorption, and post-cracking response of the specimens.

The slab specimens were prepared using the selected bendable composite mix and internal steel reinforcement. The specimens were cast using the same basic fabrication procedure and were subjected to controlled curing conditions before testing. The initial flexural test was performed to establish the load–deformation behaviour and cracking response of the specimens. After the initial testing stage, the specimens selected for rehabilitation were subjected to controlled flexural damage. The damaged specimens were then prepared for CFRP strengthening. The

CFRP sheets were externally bonded to the designated surface using the specified adhesive system. After completion of the bonding and curing process, the strengthened specimens were retested under the same flexural loading arrangement. The experimental results obtained before and after CFRP strengthening were subsequently compared to quantify the strength regain achieved through the repair and strengthening process.

The comparison included the maximum load, flexural response, maximum deformation, energy absorption, and flexural toughness of the specimens. The experimental methodology was maintained as consistently as possible for all specimens by controlling the specimen dimensions, material quantities, reinforcement arrangement, curing procedure, damage procedure, CFRP application, and testing conditions. This consistency was necessary to ensure that the observed changes in structural performance could be primarily associated with the CFRP strengthening and the investigated reinforcement condition.

3.2 Raw Materials

The materials used in the experimental investigation were selected to prepare the bendable composite (BC) slab specimens and to provide the required structural reinforcement and external strengthening. The principal materials included cementitious constituents, fine aggregate, water, internal steel reinforcement, and Carbon Fibre Reinforced Polymer (CFRP) sheets with the associated epoxy adhesive. These materials were selected to ensure that the specimens could be prepared and strengthened according to the adopted experimental procedure. The materials were handled and incorporated using consistent procedures throughout the specimen preparation and strengthening stages.

The materials were kept consistent throughout the experimental program as far as practicable so that variations in the measured structural response could be attributed primarily to the investigated reinforcement condition and the subsequent CFRP strengthening. Particular attention was given to maintaining consistency in material quantities, specimen preparation, and curing conditions. This approach

helped minimize unintended variations between the tested specimens. The same general mixing, casting, and specimen preparation procedures were followed for all slabs to maintain uniformity in the experimental process. The specimens were also prepared using the same dimensions and testing configuration to ensure meaningful comparison of their structural responses. In addition, the CFRP application procedure was maintained consistently for the strengthened specimens, including surface preparation, epoxy application, sheet placement, and curing. Such controlled experimental conditions improved the reliability and comparability of the results obtained from the different specimen configurations. The baseline BC mix was kept constant for all investigated slab specimens. The experimental variation was introduced through the specified steel reinforcement ratios of 1.0%, 1.5%, and 2.0%.

Therefore, the baseline mix represents the reference material condition, while the different reinforcement ratios constitute the experimental variable. The CFRP sheets and epoxy adhesive were subsequently used as the external strengthening system for the damaged specimens. This controlled material arrangement provided a consistent basis for comparing the structural response before and after CFRP strengthening.

3.2.1 Cement

Cement was used as the primary binding material in the preparation of the bendable composite matrix. The cement was stored under dry conditions before mixing to prevent premature hydration and deterioration of its properties. The same cement source was used throughout the experimental program to maintain consistency between the slab specimens.

3.2.2 Fine Aggregate

Fine aggregate was incorporated into the cementitious mixture as specified by the adopted mix proportions. The aggregate was maintained in a suitable condition before mixing to minimize variations in the moisture condition of the mixture.

The quantity of fine aggregate was controlled according to the established mix design. The fine aggregate was gradually added during mixing to promote uniform distribution throughout the cementitious matrix. Careful control of its proportion helped maintain the desired consistency and workability of the fresh mixture.

3.2.3 Water

Water was used for hydration of the cementitious constituents and preparation of the fresh bendable composite mixture. The quantity of water was controlled according to the adopted mix proportions. The water-to-cement ratio used in the experimental mixture was 0.5 and was maintained constant for the specimens unless otherwise specified in the mix-design table.

3.2.4 Steel Reinforcement

Internal steel reinforcement was provided in the slab specimens to contribute to the structural load-carrying capacity under flexural loading. The reinforcement arrangement was kept consistent with the experimental design, while the investigated reinforcement condition was varied according to the specimen configuration.

3.2.5 Reinforcement Arrangement

The internal steel reinforcement was arranged within the slab according to the adopted specimen detailing. The reinforcement layout includes the longitudinal and transverse reinforcement required for the experimental slab configuration. The transverse reinforcement is shown explicitly in the revised reinforcement-detail figure to clarify its location and arrangement within the slab. The reinforcement arrangement was kept consistent for the investigated specimens, while the principal experimental variation was the specified steel reinforcement ratio.

It is important to distinguish the steel reinforcement used in the present study from the polymeric fibres discussed in some of the literature on bendable cementitious composites. The reinforcement used in the investigated slab specimens was conventional internal steel reinforcement. Therefore, the reinforcement percentages

reported for the specimens represent the specified steel reinforcement condition and should not be interpreted as fibre volume fractions. The steel reinforcement ratios of 1.0%, 1.5%, and 2.0% were selected as the principal experimental variable. These three levels provide a controlled low-to-high range for examining the influence of internal steel reinforcement on the post-cracking behaviour and CFRP-assisted strength regain of the BC slabs, while keeping the other principal experimental parameters constant. The BC slab specimens were provided with conventional internal steel reinforcement according to the experimental reinforcement arrangement. The reinforcement was placed within the slab as specified in the specimen design. No separate negative/top reinforcement system or additional side reinforcement was used as an independent experimental variable.

3.3 Manufacturing of Bendable Composite Slabs

The bendable composite slab specimens were prepared in accordance with the experimental program described in this study. The fabrication procedure was kept consistent for the different specimen groups so that the influence of the investigated steel reinforcement condition and subsequent CFRP strengthening could be evaluated reliably.

Before casting, the moulds were prepared and cleaned to ensure that the required slab dimensions were maintained. The internal steel reinforcement was cut and arranged according to the reinforcement details specified for each specimen. The reinforcement was positioned within the mould at the required location and adequately supported to prevent displacement during the placement and compaction of the bendable composite mixture. The reinforcement arrangement was maintained according to the experimental configuration of each slab. The steel reinforcement used in the present study should be distinguished from discontinuous fibres that are sometimes used as constituents of bendable cementitious composites. In this experimental program, the term steel reinforcement refers specifically to the internal structural reinforcement provided within the slab specimens. The specimens were then finished at the exposed surface and left under the specified

conditions before removal from the moulds. The same casting procedure was followed for all specimen groups to minimize variations arising from fabrication. The nominal dimensions of each specimen and the corresponding reinforcement details are presented in Table 3.1. The specimens were subsequently prepared for the initial flexural loading test to establish their load-carrying and deformation behaviour. The initial test also provided the basis for introducing the controlled damaged or pre-cracked condition required for the subsequent CFRP strengthening procedure. Each specimen was identified according to its respective steel reinforcement ratio and experimental configuration. The initial flexural loading was then carried out using the specified test arrangement, while the applied load and corresponding displacement were recorded. The resulting response was used to characterize the initial condition of the specimens before CFRP strengthening. Following the controlled damage stage, the specimens were unloaded and inspected before being subjected to the surface preparation and CFRP application procedure. Figure 3.1 presents the experimental procedure adopted before CFRP strengthening of the bendable composite slabs. Initially, the slab specimens were tested under three-point bending using a Universal Testing Machine to obtain their load-deflection behaviour.

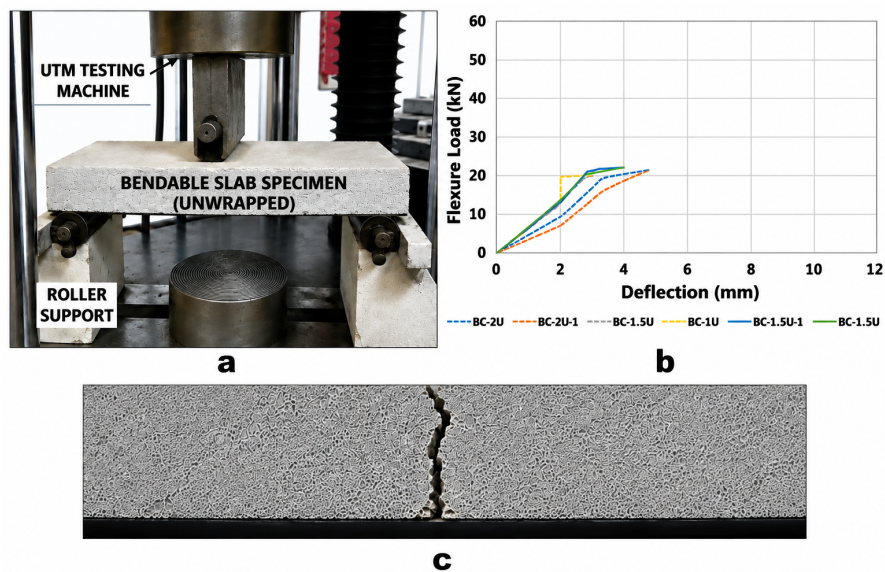


FIGURE 3.1: BC slab under UTM initial testing
a. Test Setup b. Load Deflection Curve c. Damage introduction

TABLE 3.1: Details of Bendable Composite Slab Specimens Used in the Experimental Program

Specimen ID	Steel Ratio (%)	Dimensions (mm)	Specimen Configuration	Research Purpose
BC-1-1	1.0	1000 × 500 × 100		Low steel reinforcement
BC-1-2	1.0	1000 × 500 × 100		Low steel reinforcement
BC-1.5-1	1.5	1000 × 500 × 100		Moderate steel reinforcement
BC-1.5-2	1.5	1000 × 500 × 100		Moderate steel reinforcement
BC-2-1	2.0	1000 × 500 × 100		High steel reinforcement
BC-2-2	2.0	1000 × 500 × 100		High steel reinforcement

Note: All specimens had identical dimensions. The only experimental variable was the steel reinforcement ratio.

The curves illustrate the relationship between the applied load and mid-span deflection of the unwrapped bendable composite (BC) slab specimens. In each case, the applied load increased with increasing deflection until the corresponding peak load was reached. The specimens with higher steel reinforcement ratios demonstrated slightly greater load-carrying capacity and deformation capacity compared with specimens having lower reinforcement ratios. The load–deflection response also indicates that the internal steel reinforcement contributed to maintaining load resistance after crack initiation and provided a more gradual post-cracking response. These observations indicate that the variation in steel reinforcement ratio influenced the flexural response and deformation behaviour of the unwrapped BC slabs. The curves therefore provide the baseline response of the damaged specimens before the application of CFRP strengthening. The measured load and deflection values were subsequently used for comparison with the CFRP-wrapped specimens to evaluate the improvement in flexural performance after strengthening.

(c) Crack Introduction: The photograph shows the controlled flexural crack developed in the BC slab after the initial loading test. The crack was intentionally introduced through the initial flexural loading procedure to obtain the required damaged or pre-cracked condition for the subsequent strengthening stage. The crack development was documented before the specimens were unloaded and prepared for CFRP application. These pre-cracked specimens were subsequently strengthened by bonding CFRP sheets to the tension face and retested under the same flexural loading arrangement. The comparison between the initial and strengthened responses was used to evaluate strength regain, deformation behaviour, energy absorption, and flexural performance after CFRP strengthening.

Table 3.2 summarizes the mechanical and energy-related characteristics of the unwrapped bendable composite (BC) slabs tested under flexural loading. The results demonstrate that increasing the steel reinforcement ratio generally improved the measured structural response of the slabs. The specimen with 1.0% steel reinforcement exhibited the lowest energy absorption capacity, whereas the specimens with 1.5% and 2.0% steel reinforcement showed higher values of E1, E2, and total

absorbed energy. The increase in E2 indicates a greater capacity to absorb energy after crack initiation and reflects improved post-cracking resistance.

Consequently, the FTI values also showed a modest increase, indicating an improvement in the ability of the slabs to sustain deformation after cracking. The observed cracking behaviour further supports the progressive response of the BC specimens. Rather than exhibiting an immediate loss of load-carrying capacity after crack initiation, the specimens maintained resistance with continued deformation. The internal steel reinforcement contributed to maintaining load resistance after crack initiation and helped control the development of localized flexural cracks. Among the tested specimens, the BC slab with 2.0% steel reinforcement demonstrated the highest total energy absorption, while the 1.0% reinforcement specimen showed comparatively lower energy absorption and post-cracking resistance. The results also indicate that the unwrapped specimens retained measurable load-carrying capacity after crack initiation. The gradual increase in deflection with increasing reinforcement ratio suggests improved deformation capacity under flexural loading. These baseline results provide a consistent reference for quantifying the strength regain and performance enhancement achieved through subsequent CFRP strengthening.

The peak load increased with the increase in steel reinforcement ratio, from 20.10 kN for BC-1U to 21.80 kN for BC-1.5U and 22.20 kN for BC-2U. Similarly, the flexural stress increased from 5.43 MPa to 5.89 MPa and 5.99 MPa, respectively. The measured deflection at peak load also increased from 2.20 mm for BC-1U to 2.70 mm for BC-1.5U and 3.10 mm for BC-2U, indicating greater deformation capacity with increasing reinforcement ratio. The total absorbed energy increased from 31.60 N·m for BC-1U to 39.10 N·m for BC-1.5U and 50.96 N·m for BC-2U. The FTI values were 1.14, 1.16, and 1.16, respectively, showing a modest improvement in post-cracking energy absorption. These results establish the initial flexural and energy-absorption characteristics of the unwrapped specimens and provide the reference condition for assessing the effectiveness of CFRP strengthening. The observed increase in peak load demonstrates the contribution of the higher reinforcement ratio to the flexural resistance of the BC slabs.

TABLE 3.2: Mechanical Properties, Fracture Parameters, and Failure Mechanisms of Unwrapped BC Slabs (Mean $\pm$ Standard Deviation)

S.No.	Specimen	Peak Load (kN)	Flexural Stress (MPa)	Deflection (mm)	E_1 (N.m)	E_2 (N.m)	E (N.m)	FTI (E/E_1)	Failure Mechanism
1	BC-1U	20.10 ± 0.15	5.43 ± 0.04	2.20 ± 0.05	27.60 ± 0.45	4.00 ± 0.12	31.60 ± 0.47	1.14	Multiple fine flexural cracking with crack localization near the mid-span.
2	BC-1.5U	21.80 ± 0.18	5.89 ± 0.05	2.70 ± 0.06	33.77 ± 0.58	5.33 ± 0.28	39.10 ± 0.61	1.16	Distributed multiple cracking with fibre bridging prior to localized flexural failure.
3	BC-2U	22.20 ± 0.20	5.99 ± 0.05	3.10 ± 0.07	43.96 ± 0.74	7.00 ± 0.20	50.96 ± 0.77	1.16	Stable multiple micro-cracking followed by localized flexural failure without CFRP confinement.

Note: Values are reported as mean $\pm$ standard deviation. FTI = Flexural Toughness Index.

3.3.1 Introduction of Controlled Damage

The damage stage was an essential part of the experimental program because the objective of the research was to investigate strength regain after damage rather than simply the strengthening of undamaged slabs. The prepared bendable composite slabs were first subjected to flexural loading to establish their initial structural response. Loading was continued until the predetermined damage condition was achieved. The development of cracking and the corresponding load–deformation response were monitored during this stage.

After the required level of damage had been introduced, the loading was stopped and the specimens were unloaded. The damaged specimens were then examined to identify the visible cracks and the condition of the damaged region. The damaged specimens were subsequently prepared for CFRP strengthening. This sequence ensured that the CFRP was applied to specimens that had already experienced controlled flexural damage. After strengthening and completion of the required curing period, the specimens were retested under the same experimental loading arrangement.

The complete experimental sequence can therefore be summarized as:

- i. Preparation and casting of the bendable composite slabs;
- ii. Curing of the specimens;
- iii. Initial flexural testing;
- iv. Controlled introduction of flexural damage;
- v. Unloading and inspection of the damaged specimens;
- vi. Preparation of the damaged surface;
- vii. Application of CFRP sheets;
- viii. Curing of the CFRP strengthening system; and
- ix. Retesting of the strengthened specimens.

3.4 Strengthening of Damaged Bendable Composite Slabs with CFRP Sheets

After the controlled flexural damage stage, the selected bendable composite slab specimens were strengthened using externally bonded Carbon Fibre Reinforced Polymer (CFRP) sheets. The strengthening procedure was carried out systematically to obtain proper adhesion between the CFRP sheet and the prepared surface of the damaged slab. The strengthening process consisted of surface preparation, cleaning, application of epoxy adhesive, placement of the CFRP sheet, removal of entrapped air and excess adhesive, and curing of the bonded system. The same basic procedure was followed for the strengthened specimens to maintain consistency during the experimental investigation.

TABLE 3.3: Adhesive Parameters for the CFRP Strengthening System

S.No.	Property	Value / Unit
1	Type of Adhesive	Two-component epoxy resin
2	Tensile Strength	25–35 MPa
3	Compressive Strength	60–80 MPa
4	Elastic Modulus	3–5 GPa
5	Bond Strength to Concrete	2.0–3.5 MPa
6	Pot Life (at 25°C)	30–45 min
7	Curing Time	24–48 h
8	Density	1.1–1.3 g/cm ³

Source: Values provided by the adhesive manufacturer.

3.4.1 Surface Preparation

Before applying the CFRP sheets, the surface of each damaged slab was carefully prepared to ensure a clean, smooth, and suitable bonding surface. Loose particles, dust, laitance, and other contaminants were removed from the strengthening area. The damaged surface was then visually inspected to identify visible cracks, uneven regions, and other surface irregularities. Where required, mechanical surface preparation was carried out to improve the contact and bond between the

TABLE 3.4: Composition and Properties of Carbon Fibre Reinforced Polymer (CFRP)

Property	Symbol / Unit	Typical Value / Description
Fiber Type	–	High-Strength Carbon Fiber
Fiber Orientation	–	Unidirectional
Density	ρ (g/cm ³)	1.6–1.8
Tensile Strength	f_t (MPa)	3800–4200
Elastic Modulus	E (GPa)	230–250
Ultimate Strain	ε_u (%)	1.5–1.7
Sheet Thickness	t (mm)	0.111–0.167
Resin Type	–	Two-Component Epoxy Adhesive
Tensile Strength of Resin	f_r (MPa)	60–75
Glass Transition Temperature	T_g (°C)	60–80
Bonding Method	–	Externally Bonded Using Epoxy Resin
Water Absorption	–	< 0.5%
Corrosion Resistance	–	Excellent (Non-Metallic)
Operating Temperature Range	–	–20°C to +80°C

Source: Values provided by the CFRP manufacturer.

cementitious substrate and the epoxy adhesive. After mechanical preparation, the surface was thoroughly cleaned to remove any remaining dust or debris. The prepared surface was then allowed to reach the appropriate condition before the epoxy adhesive was applied and the CFRP sheet was installed. Particular attention was given to ensuring that the bonding surface was free from moisture, loose material, and other substances that could adversely affect adhesion. A properly prepared substrate was considered essential for achieving effective stress transfer between the damaged slab and the externally bonded CFRP sheet. The prepared surface was also checked for local depressions or projections that could interfere with the uniform placement of the CFRP sheet. Any minor surface defects within

the strengthening zone were corrected where necessary before adhesive application. This preparation procedure helped ensure continuous contact between the CFRP sheet and the slab surface and promoted reliable transfer of stresses during subsequent flexural loading.

3.4.2 Depiction of CFRP Sheets and Their Cut Lengths

The robust, thin fabric sheets known as Carbon Fibre Reinforced Polymer (CFRP) are made from carbon fibers. Because these fibers are only oriented in one way, they can withstand extremely high pulling pressures. When CFRP sheets are attached to the bottom of concrete or ECC slabs, they assist the slabs become stronger once cracks appear. Before being affixed to the slab, the CFRP sheets are carefully cut to the correct dimensions. The length of the sheet is chosen to extend slightly on both sides and cover the cracked area.

TABLE 3.5: Details of CFRP-Wrapped Bendable Composite (BC) Slab Specimens and Strengthening Configuration

Specimen ID	Steel Ratio (%)	CFRP	Zone	L (mm)	W (mm)	t (mm)	Layers
BC-1W	1.0	Yes	Bottom	1000	500	0.111	1
BC-1W-1	1.0	Yes	Bottom	1000	500	0.111	1
BC-1.5W	1.5	Yes	Bottom	1000	500	0.111	1
BC-1.5W-1	1.5	Yes	Bottom	1000	500	0.111	1
BC-2W	2.0	Yes	Bottom	1000	500	0.111	1
BC-2W-1	2.0	Yes	Bottom	1000	500	0.111	1

Note: CFRP sheets were externally bonded to the bottom (tension) face of the BC slabs. All specimens were strengthened using a single CFRP layer.

3.4.3 Wrapping of Specimens

In order to successfully restore the mechanical properties of the composite, the wrapping process for recovering damaged specimens with Carbon Fiber Reinforced



FIGURE 3.2: CFRP sheets

Polymer (CFRP) sheets entails a number of painstakingly carried out steps. Surface preparation is the first step in the procedure to ensure that the damaged composite and the CFRP sheet adhere well to one another. The damaged area is first thoroughly cleaned to remove any loose particles, dirt, or debris that could impede the bonding process. The surface is next lightly sanded or ground to create a rough surface that enhances the mechanical interlocking of the glue. To create a perfect bonding surface, any remaining impurities are next removed by washing the surface with a solvent. It is mixed in accordance with the manufacturer's instructions and is selected for its robust bonding qualities and compatibility with CFRP sheets. Using a trowel or brush, the prepared surface is then uniformly filled with glue, making sure to cover the whole area that needs to be wrapped. Gaps, uneven thickness, and excessive glue are avoided since they may generate weak areas in the binding.

Carefully placed on top of the adhesive is the CFRP sheet, which has been pre-cut to fit the measurements of the damaged region. The CFRP sheet's fiber orientation is intentionally orientated to manage particular stress conditions in the composite, depending on the structural needs.

The application of CFRP sheets was carried out carefully to ensure proper alignment and adequate contact with the prepared surface. Depending on the mechanical performance requirements of the repair, multiple layers of CFRP sheets may be applied, with each layer properly aligned, pressed, and bonded before proceeding to the next layer. The CFRP sheets were also positioned according to the specimen



FIGURE 3.3: step by step strengthening of BC slab

geometry, particularly where curved or irregular surfaces required careful handling to achieve effective coverage. Proper placement of the sheets helped ensure efficient transfer of stresses between the CFRP and the composite material. The curing process determines the maximum strength of the bond between the CFRP sheet and the composite material. The wrapped specimens were therefore left to cure under controlled conditions in accordance with the recommendations for the adhesive system. Adequate curing allowed the adhesive to develop sufficient bonding strength and durability before mechanical testing. After curing, the repaired specimens were carefully inspected to identify possible defects such as delamination, air pockets, wrinkles, or uneven bonding. Any visible defects were addressed where necessary to ensure the quality and continuity of the strengthening system.

Finally, the repaired specimens were mechanically tested to evaluate the extent to which their load-carrying capacity, deformation response, and overall flexural performance were restored. The comparison between the damaged and CFRP-strengthened specimens provided a basis for assessing the effectiveness of the repair technique. This procedure ensured that the CFRP sheets were securely bonded and capable of contributing to the structural response of the damaged

bendable composite specimens. The retesting results were also used to quantify the changes in peak load, flexural stress, deformation, and energy absorption following strengthening. These measurements enabled a direct assessment of the strength regain achieved through the application of CFRP sheets.

3.5 Test Setup for Strength Regain Measurement

The flexural performance of the bendable composite slab specimens was evaluated using the laboratory loading frame. The same basic testing arrangement was maintained during the initial testing and the subsequent testing of the CFRP-strengthened specimens so that the changes in structural response could be compared. The slab specimen was positioned on the supports of the loading frame and the load was applied at the designated loading location. The applied load and corresponding mid-span deformation were recorded throughout the test. The test was continued until the specimen reached its ultimate load and the subsequent failure behaviour could be observed. The testing arrangement was selected to evaluate the flexural response of the slab under controlled loading. Particular attention was given to the maximum load, deformation at the maximum load, and the load–deformation relationship obtained during the test.

3.5.1 Flexural Loading Arrangement

The slab specimens were tested under the flexural loading arrangement shown in Figure 3.4. The support and loading configuration was kept consistent for the specimens tested before and after CFRP strengthening. The specimen was placed symmetrically on the supports, and the load was applied at the specified loading point. The loading arrangement was selected to produce flexural action in the central region of the slab. The applied load was increased progressively while the corresponding deformation was monitored. The load–deformation response was recorded until the specimen reached its maximum load and the subsequent failure response was observed. The same testing procedure was followed for both the

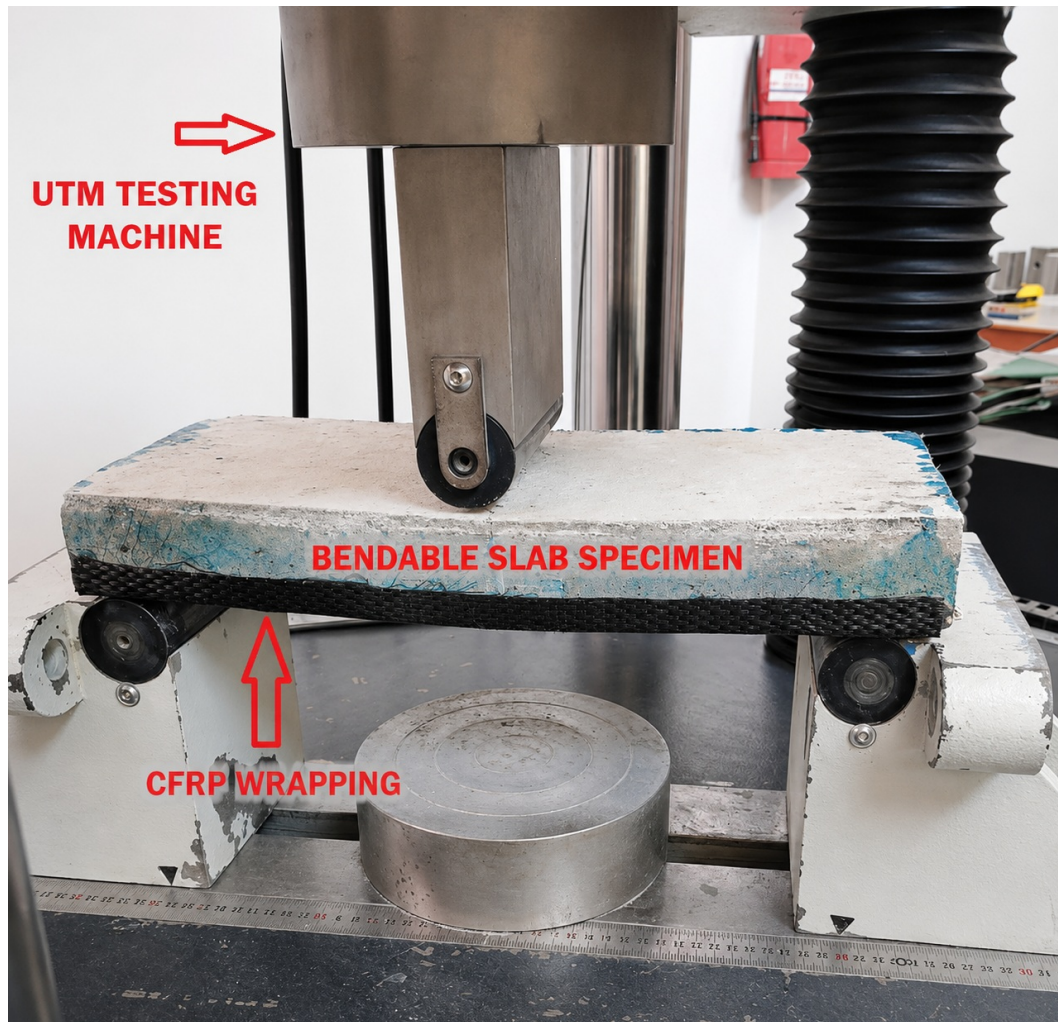


FIGURE 3.4: BC slab under UTM initial testing
Test Setup

initially tested and CFRP-strengthened specimens to ensure meaningful comparison of their structural responses. The maximum applied load and corresponding deformation were noted for each specimen during the test. The recorded experimental data were subsequently used to evaluate the flexural strength, deformation behaviour, and strength regain achieved through CFRP strengthening.

3.5.2 Load Measurement

The applied load was measured using the calibrated load-measuring system associated with the laboratory loading frame. The load was recorded continuously

during the test to obtain the complete load–deformation response of each specimen. The maximum recorded load was taken as the peak load of the specimen. The peak load obtained from the initial test was used as the reference for evaluating the subsequent response of the CFRP-strengthened specimen. The same loading system and testing procedure were used for the relevant specimens to minimize experimental variations between the initial and post-strengthening tests. The load response was monitored throughout the test to identify the initiation of cracking and subsequent changes in the flexural behaviour. The recorded peak-load values were used for comparison among specimens with different reinforcement ratios. This approach provided a consistent basis for assessing the changes in load-carrying capacity after CFRP strengthening

3.5.3 Measurement of Mid-Span Deflection Using LVDT

The vertical deformation of the slab was measured at the mid-span using a Linear Variable Differential Transformer (LVDT). An LVDT is an electromechanical displacement transducer used to measure linear movement with high sensitivity. The LVDT was positioned at the mid-span region of the specimen so that the vertical displacement produced by the applied flexural load could be recorded. The measured displacement was recorded together with the corresponding applied load. The resulting load–deflection data were used to develop the load–deformation curves for the tested specimens. These curves were subsequently used to determine the peak load, maximum deformation, and energy-related parameters required for evaluation of the strength-regain behaviour.

3.6 Parameters to be Explored

The experimental investigation was conducted to evaluate the structural response of bendable composite slabs before and after CFRP strengthening. The parameters selected for evaluation were based on the load–deformation response obtained during flexural testing. The principal parameters considered in the experimental

investigation were peak load, flexural strength, maximum deformation, energy absorption, and Flexural Toughness Index (FTI). These parameters were used to quantify the change in structural performance resulting from CFRP strengthening.

3.6.1 Peak Load

The peak load was defined as the maximum load sustained by a specimen during the flexural test. The peak load obtained from the load–deformation curve was used to compare the load-carrying capacity of the specimens before and after CFRP strengthening. For each specimen, the corresponding deformation at peak load was also recorded to assess its flexural deformation behaviour. The peak load values provided a direct measure of the change in structural capacity resulting from CFRP strengthening.

3.6.2 Flexural Strength

Flexural strength was determined from the measured peak load and the geometrical and loading parameters of the tested slab specimens. The calculated flexural strength was used to evaluate the change in flexural capacity associated with CFRP strengthening.

3.6.3 Maximum Deformation

Maximum deformation represents the largest recorded vertical displacement of the specimen during the flexural test. The deformation response was obtained using the displacement measurement system positioned at the mid-span. Comparison of deformation before and after strengthening was used to assess the change in deformation capacity of the slabs.

3.6.4 Energy Absorption

Energy absorption was evaluated from the area under the experimental load–deformation curve. The area was calculated over the specified portions of the curve

and was used to quantify the energy-related response of the specimens. The energy parameters were subsequently used in the calculation of the Flexural Toughness Index.

3.6.5 Flexural Toughness Index

The Flexural Toughness Index (FTI) was used to evaluate the relationship between the total energy absorbed by the specimen and the corresponding reference energy obtained from the load–deformation response.

The FTI was calculated using:

$$FTI = \frac{E}{E_1} \quad (3.1)$$

where:

- E = total energy represented by specified area under the load–deformation curve; and
- E_1 = reference energy corresponding to the initial specified portion of the load–deformation curve.

The calculated FTI values were compared among the investigated specimens to assess the effect of CFRP strengthening on the post-cracking and energy absorption behaviour of the bendable composite slabs.

3.6.5.1 Strength Regain

The principal objective of the experimental investigation was to quantify the strength regained after CFRP strengthening. The strength regain was evaluated by comparing the peak load of the strengthened specimen with the corresponding reference condition.

The percentage strength regain was calculated as:

$$\text{Strength Regain (\%)} = \frac{P_{\text{strengthened}} - P_{\text{reference}}}{P_{\text{reference}}} \times 100 \quad (3.2)$$

where:

- $P_{\text{strengthened}}$ = peak load of the CFRP-strengthened specimen; and
- $P_{\text{reference}}$ = corresponding reference peak load.

The calculated strength-regain values, together with the deformation, energy, and FTI parameters, were used to assess the effectiveness of CFRP sheets in recovering the flexural performance of damaged bendable composite slabs.

3.6.6 Ductility Assessment

The ductility behaviour of the BC slab specimens was assessed from the load–deflection response obtained during flexural testing. Particular attention was given to the measured displacement capacity and the post-cracking behaviour of the specimens. The CFRP-wrapped specimens were compared with the corresponding unwrapped specimens to assess changes in deformation capacity and overall flexural behaviour. A conventional yield displacement was not assigned because a distinct yield point was not experimentally established for the tested BC slab specimens.

3.7 Summary

This chapter presented the experimental methodology adopted to investigate the strength regain of damaged bendable composite (BC) slabs strengthened with Carbon Fibre Reinforced Polymer (CFRP) sheets. It described the selection and characterization of the constituent materials, including cement, fine aggregates, steel reinforcement, epoxy adhesive, and CFRP sheets, along with the procedures used for specimen casting, curing, and quality control. The chapter also detailed the fabrication of bendable composite slabs with different steel reinforcement contents and explained the methodology used to introduce controlled flexural cracks

before rehabilitation. Furthermore, the procedures for surface preparation, CFRP sheet application, epoxy bonding, and curing of the strengthened specimens were explained. The subsequent flexural testing procedure was described to ensure consistent comparison between the damaged and CFRP-strengthened slabs. The measured parameters included peak load, flexural stress, deformation, energy absorption, and Flexural Toughness Index (FTI), which were used to evaluate the effectiveness of the strengthening technique. The experimental program also included the systematic comparison of unwrapped and CFRP-wrapped specimens under the same flexural loading conditions. The collected results provided a basis for determining the extent of strength recovery after rehabilitation.

Chapter 4

Experimental Testing Outcomes

4.1 Background

This chapter presents the experimental testing outcomes obtained from the damaged bendable composite (BC) slab specimens before and after strengthening with externally bonded carbon fibre reinforced polymer (CFRP) sheets. The purpose of the experimental investigation was to evaluate the extent to which CFRP strengthening could restore the flexural performance of the damaged specimens. The assessment was based on the measured structural response under flexural loading and focused on the parameters selected in Chapter 3. The experimental results are evaluated using the load–deformation response, peak load, flexural stress, deformation at peak load, energy absorption, and Flexural Toughness Index (FTI). These parameters provide a quantitative basis for comparing the behaviour of the damaged unwrapped specimens with that of the corresponding CFRP-wrapped specimens. The comparison was carried out for the investigated steel reinforcement conditions so that the influence of CFRP strengthening could be examined consistently. The load–deformation response provides an important indication of the behaviour of the specimens throughout the loading process. The initial portion of the curve represents the response before significant cracking, while subsequent changes in the slope reflect the development of cracks and changes in stiffness. The maximum point of the curve represents the peak load sustained by the specimen, whereas

the deformation corresponding to the maximum load provides an indication of its deformation capacity. For the strengthened specimens, the load–deformation curves were therefore used to assess changes in load-carrying capacity and post-cracking behaviour resulting from the application of CFRP sheets. The flexural strength results are used to quantify the improvement in load-carrying capacity after strengthening. The peak loads obtained from the experimental tests are compared with the corresponding values of the damaged unwrapped specimens. Similarly, flexural stress values are compared to determine the change in flexural performance associated with CFRP strengthening. The percentage strength regain is subsequently used to express the improvement in structural capacity in a quantitative form.

Finally, the results obtained from the experimental investigation are compared across the different steel reinforcement conditions. The purpose of this comparison is not only to identify the specimen with the highest measured strength but also to examine the variation in strength regain, deformation response, energy absorption, and FTI. The experimental findings presented in this chapter form the basis for the discussion of the empirical relationship and practical implementation presented in Chapter 5.

The steel reinforcement ratio was considered the principal experimental variable in this study. Three reinforcement ratios, namely 1.0%, 1.5%, and 2.0%, were investigated while the other principal experimental conditions were maintained consistently. The measured parameters, including peak load, strength regain, flexural stress, deformation, energy absorption, and Flexural Toughness Index (FTI), were treated as response parameters for evaluating the influence of the reinforcement ratio and CFRP strengthening. Therefore, the steel reinforcement ratio represents the critical experimental factor, while the remaining parameters describe the resulting structural response. The comparison of these parameters provides a comprehensive assessment of the influence of reinforcement ratio on the flexural behaviour of the BC slabs. The results also allow the relative effectiveness of CFRP strengthening to be examined for each reinforcement condition. Particular attention is given to the changes in peak load and deformation response before and

after CFRP strengthening. The energy absorption and FTI results further provide an indication of the post-cracking behaviour of the strengthened specimens.

4.2 Load–Deflection Curves of Wrapped BC Slabs

The load–deformation response of slab specimens was analyzed to evaluate structural stiffness and ductility characteristics. The typical flexural behavior of Bendable Concrete slabs can be divided into three stages: the initial linear elastic stage, the crack development stage, and the ultimate failure stage. For uncracked slabs, a nearly linear response was observed until first cracking occurred, followed by gradual stiffness reduction. In pre-cracked damaged slabs, stiffness degradation was more pronounced due to existing cracks.

However, CFRP-strengthened slabs exhibited improved post-cracking stiffness and delayed failure compared to damaged specimens. The strengthened slabs demonstrated higher ultimate deflection capacity before failure, indicating improved ductility. The shift in load–deformation curves toward higher load levels confirms the effectiveness of CFRP sheets in restoring structural performance.

The load–deflection curves obtained from the experimental program clearly demonstrate the progressive improvement in structural response with increasing steel ratio in bendable concrete slabs. The unwrapped specimens exhibited an initial linear elastic response up to the cracking load, followed by a gradual nonlinear region indicating micro-crack propagation and strain hardening behavior. Among the unwrapped specimens, the 1% steel slab showed improved peak load compared to plain bendable concrete, while the 1.5% and 2% steel slabs demonstrated significantly higher peak loads and enhanced deformation capacity. The 2% steel specimen achieved the highest ultimate load among the unwrapped samples, indicating that increased reinforcement ratio contributes to better stress redistribution and crack control.

Additionally, the post-peak response of higher steel ratio slabs was more gradual, reflecting improved ductility and energy absorption capacity. The CFRP-wrapped

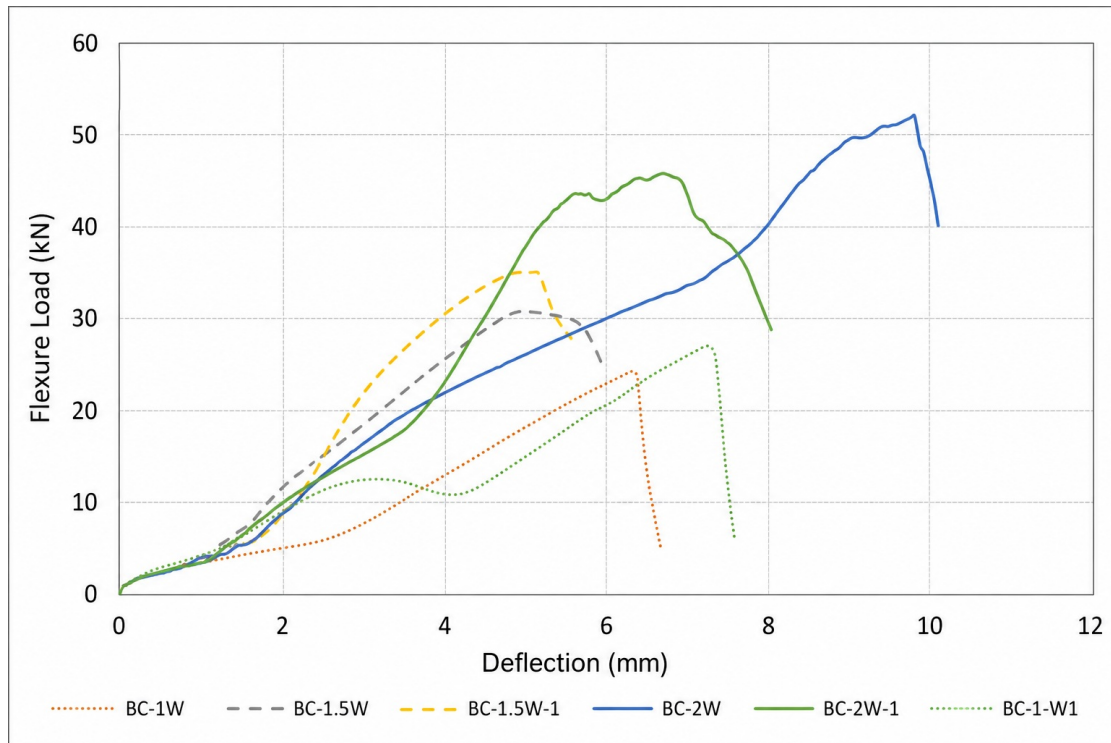


FIGURE 4.1: Load–deflection curve of CFRP-wrapped samples

specimens exhibited a notable enhancement in both peak load and deflection capacity compared to their corresponding unwrapped slabs. The strengthening effect of externally bonded CFRP sheets resulted in delayed crack widening, increased stiffness after cracking, and higher ultimate load levels. The wrapped 1.5% and 2% steel specimens showed the most stable post-peak behavior, indicating improved confinement and fracture resistance.

The area under the load–deflection curves for wrapped slabs was considerably larger, signifying higher energy absorption and fracture toughness index (FTI) values. Overall, the load–deflection response confirms that the combined action of internal steel reinforcement and external CFRP wrapping significantly enhances the strength, ductility, and structural resilience of bendable concrete slabs. The Fracture Toughness Index (FTI) is a parameter used to evaluate the energy absorption capacity and post-cracking performance of bendable concrete slabs. Unlike conventional concrete, which fails in a brittle manner after reaching peak stress, bendable concrete exhibits strain-hardening and multiple cracking behavior. The FTI helps quantify this ductility by comparing the total energy absorbed by the

specimen to the energy absorbed up to first cracking. In stress–strain terms, this energy corresponds to the area under the stress–strain curve. A higher FTI value indicates improved toughness, better crack control, and enhanced resistance to sudden failure, which are essential characteristics for structural elements subjected to flexural and dynamic loading. Mathematically, the Fracture Toughness Index is expressed as: Where E is the total fracture toughness of the specimen up to failure and $[Symbol]$ is the fracture toughness at first cracking. Both parameters are obtained from the stress–strain response by integrating stress over the corresponding strain range. These values represent the material’s ability to absorb deformation and resist crack propagation under loading.

The evaluation of strength regain in CFRP-strengthened bendable composite (BC) slabs was performed through a systematic assessment of multiple structural performance indicators. Rather than relying solely on ultimate load comparison, this study considered a combination of mechanical response parameters to comprehensively understand the effectiveness of the strengthening intervention. The parameters analyzed include cracking behavior, ultimate load capacity, stiffness characteristics, deformation response, ductility performance, load redistribution capability, and failure mechanisms. These parameters collectively provide a holistic measure of structural recovery after damage.

4.3 Fracture Mechanism

The fracture behaviour of the CFRP-wrapped bendable composite (BC) slabs was examined during the flexural tests to identify the progression of cracking and the final failure condition of the strengthened specimens. The observed failure mechanisms provide an understanding of the interaction between the existing steel reinforcement, the bendable composite material, and the externally bonded CFRP sheets. At the initial stage of loading, the specimens responded primarily through flexural deformation. With increasing applied load, flexural cracks developed in the tension region of the slabs. As the load increased further, the cracks became more pronounced and propagated through the critical flexural zone. The presence

of the CFRP sheet provided additional tensile resistance across the cracked region and contributed to maintaining the load-carrying capacity after cracking.

For specimen BC-1W, flexural cracking was observed before localized separation of the CFRP strengthening system from the substrate. The failure was therefore associated with flexural cracking followed by CFRP debonding. In BC-1.5W, multiple flexural cracks developed before CFRP debonding occurred, indicating that the strengthened specimen continued to sustain load after the formation of several cracks. For BC-2W, flexural failure was accompanied by localized CFRP debonding. The failure observations for the three wrapped specimens are summarized in Table 4.1.

The observed failure mechanisms demonstrate that the CFRP sheet remained involved in the structural response after the development of flexural cracks. However, the effectiveness of the strengthening system was also dependent on the bond between the CFRP sheet and the prepared concrete surface. Localized debonding reduced the ability of the CFRP sheet to continue contributing its full tensile resistance and ultimately contributed to the failure of the strengthened specimens.

4.4 Strength Regain Evaluation Parameters

The effectiveness of CFRP strengthening was evaluated by comparing the experimental response of the damaged unwrapped bendable composite (BC) slabs with that of the corresponding CFRP-wrapped slabs. The assessment was based on the principal parameters obtained from the flexural tests, including peak load, flexural stress, deformation, energy absorption, and Flexural Toughness Index (FTI). These parameters provide a quantitative basis for determining the extent of strength regain achieved after CFRP strengthening. Peak load represents the maximum load sustained by a specimen during the flexural test before failure. Comparison of the peak load values of the unwrapped and CFRP-wrapped specimens provides a direct measure of the improvement in load-carrying capacity

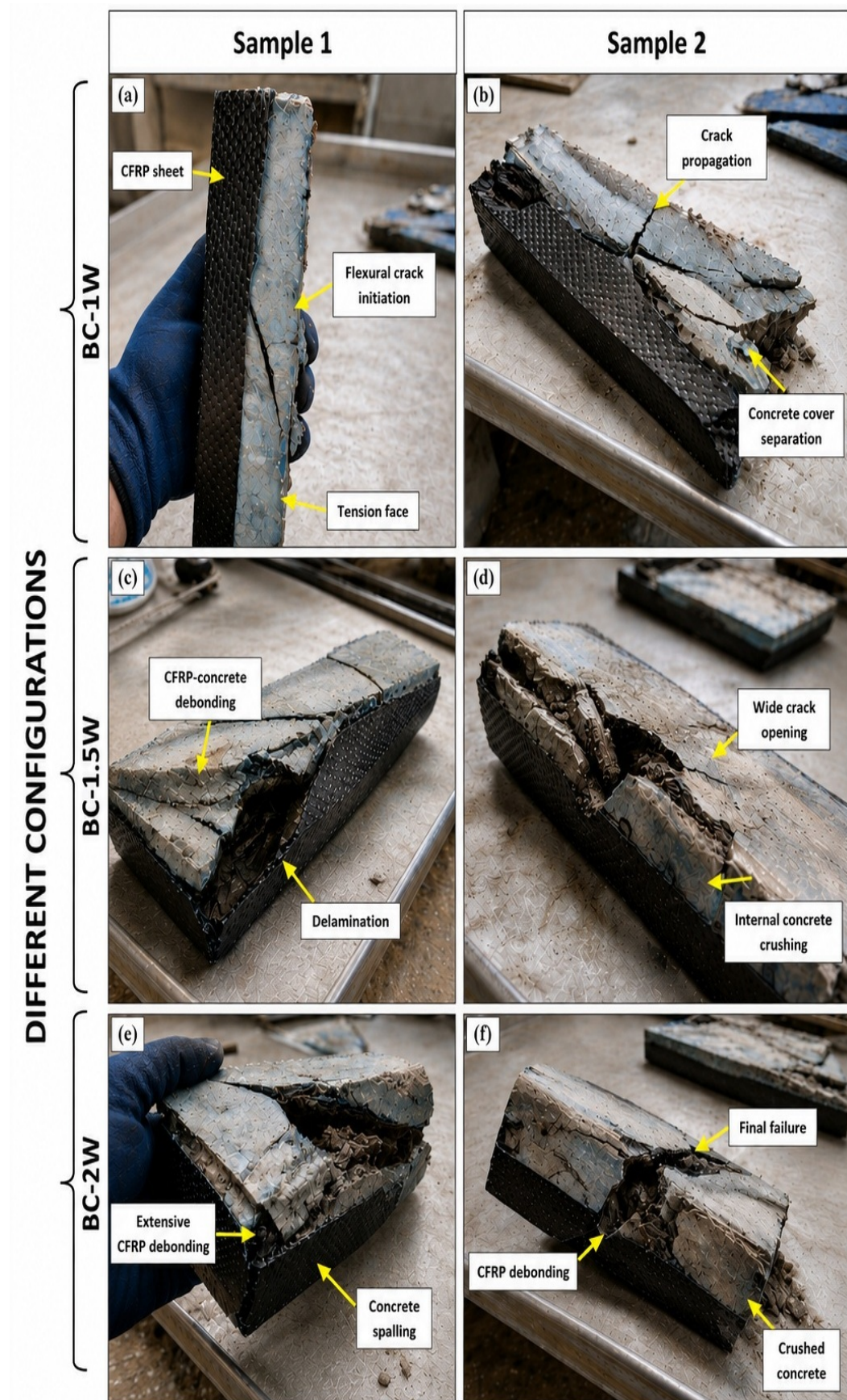


FIGURE 4.2: Failure observed in wrapped samples

These values demonstrate the contribution of the externally bonded CFRP sheet to the flexural resistance of the damaged specimens.

Flexural stress was determined from the measured peak load and specimen geometry to provide a normalized measure of flexural performance. The comparison between unwrapped and wrapped specimens indicates that CFRP strengthening increased the flexural stress for all investigated conditions. The flexural stress increased from 5.43 MPa to 7.04 MPa for BC-1, from 5.89 MPa to 8.95 MPa for BC-1.5, and from 5.99 MPa to 13.10 MPa for BC-2 after CFRP strengthening. The results indicate that the CFRP sheet provided additional tensile resistance in the cracked region and consequently improved the flexural load-carrying capacity of the damaged slabs. The deformation corresponding to the maximum applied load was recorded during the flexural tests.

This parameter was used to examine the deformation response of the strengthened specimens in comparison with the corresponding unwrapped specimens. The CFRP-wrapped specimens exhibited different deformation responses depending on the investigated steel reinforcement condition. These differences indicate that CFRP strengthening affected not only the maximum load capacity but also the manner in which the specimens responded to increasing deformation. The deformation results are therefore considered together with the load–deformation curves and failure observations rather than being used independently to define ductility. Energy absorption was determined from the area under the load–deformation curve. It represents the amount of mechanical energy absorbed by the specimen during the loading process up to the considered failure condition. The total energy absorption was obtained from the relevant energy components:

$$E = E_1 + E_2$$

where E_1 and E_2 represent the respective areas considered in the load–deformation response. The comparison presented in Figure 4.3 shows that CFRP wrapping substantially increased the energy absorbed by the damaged specimens. The total energy increased from 31.60 J to 101.83 J for BC-1, from 39.10 J to 106.10 J for BC-1.5, and from 50.96 J to 240.90 J for BC-2. These increases indicate that the

strengthened specimens were able to sustain greater loading over the deformation range before reaching their final failure condition. The improvement in energy absorption is attributed to the additional tensile resistance provided by the externally bonded CFRP sheet and its contribution to the post-cracking response. The Flexural Toughness Index (FTI) was used to evaluate the relative contribution of the different portions of the load–deformation response to the overall toughness of the specimens. It was calculated using:

$$FTI = \frac{E}{E_1}$$

where E is the total energy obtained from the load–deformation response and E_1 is the specified initial energy component. The calculated FTI values for the CFRP-wrapped specimens were 1.18 for BC-1W, 1.29 for BC-1.5W, and 1.22 for BC-2W. The results indicate that the CFRP-strengthened specimens maintained a substantial contribution from the post-cracking portion of the response. The FTI values greater than unity indicate that the total absorbed energy exceeded the specified initial energy component for all strengthened specimens. The BC-1.5W specimen exhibited the highest FTI value among the investigated CFRP-wrapped configurations. This indicates a comparatively greater contribution of the post-cracking response to the overall energy absorption of this specimen. The BC-1W and BC-2W specimens also demonstrated considerable energy absorption beyond the initial response. The variation in FTI values suggests that the internal steel reinforcement ratio influences the energy absorption behaviour of the strengthened slabs. CFRP strengthening contributed to maintaining load resistance after cracking and improved the overall post-cracking response.

Therefore, FTI provides an additional parameter for assessing the effectiveness of CFRP rehabilitation beyond peak load and flexural strength alone. The FTI results also provide a basis for comparing the post-cracking behaviour of the different reinforcement configurations. The relatively higher FTI value of BC-1.5W indicates a greater proportion of energy absorption in the post-cracking region compared with BC-1W and BC-2W. This behaviour can be attributed to the combined action of the internal steel reinforcement and the externally bonded CFRP sheet

in resisting tensile stresses after cracking. The CFRP sheet provides additional tensile resistance across the damaged region, while the internal reinforcement continues to contribute to the overall flexural response. The interaction between these two strengthening components helps maintain load-carrying capacity after the initiation of cracking. It also contributes to improved control of crack propagation during subsequent loading. The post-cracking energy absorption reflects the ability of the strengthened specimen to sustain additional deformation while continuing to carry load. The observed FTI values therefore provide an indication of the improved toughness of the repaired specimens. The results further suggest that the effectiveness of CFRP strengthening is influenced by the existing reinforcement configuration within the composite.

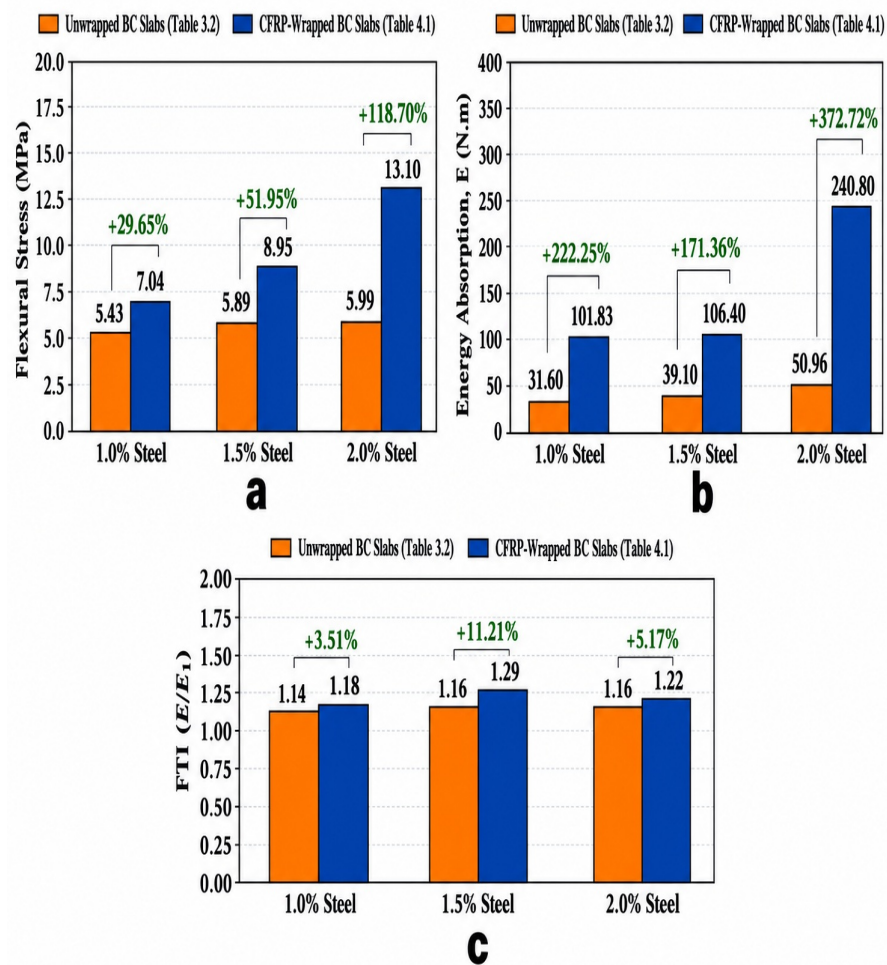


FIGURE 4.3: Comparison of properties of Wrapped and Unwrapped Samples
a.Flexural strength b.Energy Absorption c.FTI

TABLE 4.1: Mechanical Properties, Fracture Parameters, and Failure Mechanisms of CFRP-Wrapped BC Slabs (Mean $\pm$ Standard Deviation)

S.No.	Specimen	Peak Load (kN)	Flexural Stress (MPa)	Deflection (mm)	E_1 (N.m)	E_2 (N.m)	E (N.m)	FTI (E/E_1)	Failure Mechanism
1	BC-1W	26.09 $\pm$ 0.21	7.04 $\pm$ 0.06	6.90 $\pm$ 0.15	86.01 $\pm$ 0.75	15.82 $\pm$ 0.25	101.83 $\pm$ 0.79	1.18	Flexural cracking accompanied by partial CFRP debonding.
2	BC-1.5W	33.16 $\pm$ 0.32	8.95 $\pm$ 0.09	5.14 $\pm$ 0.12	82.50 $\pm$ 0.70	23.60 $\pm$ 0.30	106.10 $\pm$ 0.76	1.29	Multiple flexural cracking with delayed CFRP debonding.
3	BC-2W	48.51 $\pm$ 0.45	13.10 $\pm$ 0.12	8.33 $\pm$ 0.18	198.10 $\pm$ 1.10	42.80 $\pm$ 0.45	240.90 $\pm$ 1.19	1.22	Flexural failure associated with localized CFRP debonding.

Note: Values are reported as mean $\pm$ standard deviation. FTI denotes the Flexural Toughness Index.

4.5 Summary

This chapter presented and discussed the experimental results obtained from the flexural testing of damaged bendable composite (BC) slabs before and after strengthening with externally bonded carbon fibre reinforced polymer (CFRP) sheets. The behaviour of the specimens was evaluated using load–deformation response, peak load, flexural stress, deformation, energy absorption, and Flexural Toughness Index (FTI). The load–deformation results showed that CFRP strengthening improved the load-carrying response of the damaged BC slabs. The strengthened specimens sustained higher peak loads than the corresponding unwrapped specimens, demonstrating the contribution of the externally bonded CFRP sheets to the flexural resistance of the damaged slabs. The magnitude of improvement varied with the investigated steel reinforcement condition. The comparison of flexural stress also confirmed an improvement after CFRP strengthening. The flexural stress increased from 5.43 MPa to 7.04 MPa for BC-1, from 5.89 MPa to 8.95 MPa for BC-1.5, and from 5.99 MPa to 13.10 MPa for BC-2. CFRP strengthening also resulted in substantially higher energy absorption. The total energy increased from 31.60 J to 101.83 J for BC-1, from 39.10 J to 106.10 J for BC-1.5, and from 50.96 J to 240.90 J for BC-2. The FTI values of the wrapped specimens were 1.18, 1.29, and 1.22 for BC-1W, BC-1.5W, and BC-2W, respectively. The observed failure mechanisms were primarily associated with flexural cracking followed by localized CFRP debonding. The experimental findings demonstrate that CFRP wrapping can improve the flexural performance and energy absorption of damaged BC slabs. The results obtained in this chapter provide the experimental basis for the development and discussion of the empirical relationship presented in Chapter 5.

Chapter 5

Discussion and Guidelines for Practical Implementations

5.1 Background

The experimental investigation presented in Chapter 4 evaluated the flexural response of damaged bendable composite (BC) slabs before and after strengthening with externally bonded Carbon Fibre Reinforced Polymer (CFRP) sheets. The experimental results showed that CFRP strengthening increased the measured peak load, flexural stress, deformation capacity, energy absorption, and post-cracking performance of the investigated specimens. The magnitude of the improvement varied with the steel reinforcement ratio. In addition to the experimental comparison, an empirical relationship was developed to provide a simple mathematical representation of the measured peak-load response of the CFRP-strengthened BC slabs. The purpose of this relationship is to describe the observed trend within the experimental range investigated in this study and to provide a preliminary estimation of peak load for specimens having conditions comparable to those tested experimentally.

The empirical relationship was developed using the measured peak-load results of the CFRP-strengthened specimens corresponding to the investigated steel reinforcement ratios. Because the experimental dataset is limited, the equation

should be regarded as an empirical relationship for the investigated experimental range rather than a universally validated predictive design equation. Independent experimental validation using additional specimens and reinforcement conditions would be required before applying the relationship to structural systems outside the present experimental program. The chapter also discusses the practical implementation of CFRP strengthening for damaged BC slabs. Particular attention is given to assessment of the damaged member, surface preparation, epoxy bonding, CFRP placement, curing, inspection, and limitations on the application of the proposed empirical relationship.

5.2 Development of Empirical Relationship

A preliminary empirical relationship was developed to describe the relationship between the adopted steel reinforcement ratio and the measured peak load of the CFRP-strengthened BC slabs. A second-order polynomial form was selected because the three experimental observations did not indicate a strictly linear change in peak load with increasing steel reinforcement ratio. The purpose of this relationship is to provide a preliminary mathematical representation of the experimental trend within the investigated range rather than to establish a general design equation.

$$P_{u,\text{pred}} = aX^2 + bX + c \quad (5.1)$$

where:

Based on the experimental results obtained from the CFRP-strengthened BC slab specimens, an empirical polynomial relationship was developed to represent the variation of peak load with the investigated steel reinforcement ratio. The relationship was developed using the measured peak-load values corresponding to steel reinforcement ratios of 1.0

The proposed second-order polynomial relationship is expressed as:

$$P_{u,\text{pred}} = 16.56X^2 - 27.26X + 36.79 \quad (5.2)$$

where $P_{u,\text{pred}}$ is the predicted peak load in kN and X represents the steel reinforcement ratio used in the investigated relationship. In the present study, X takes the numerical values 1.0, 1.5, and 2.0, corresponding to the investigated steel reinforcement ratios. The coefficients of the polynomial were obtained by fitting the relationship to the measured peak-load data. Since only three experimental points were available for the regression, the second-order polynomial provides an exact mathematical representation of these three observations. Therefore, the resulting relationship should be interpreted as a preliminary empirical representation of the experimental trend within the investigated range rather than as an independently validated predictive design equation. The relationship is applicable only within the experimental range investigated in this study and should not be extrapolated to substantially different material properties, specimen dimensions, reinforcement ratios, CFRP configurations, or loading conditions without additional experimental verification.

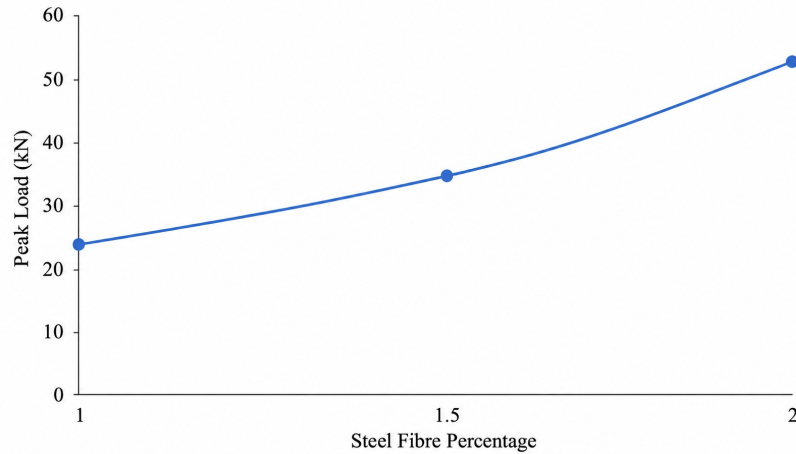


FIGURE 5.1: Polynomial trendline illustrating the empirical relationship between the selected independent variable and the predicted peak load.

The predictive capability of the proposed empirical equation was evaluated by comparing the experimentally measured peak loads with the corresponding predicted values. The comparison provides an assessment of the accuracy and reliability of the developed model for estimating the flexural capacity of CFRP-strengthened

bendable composite slabs. The comparison presented in Table 5.1 demonstrates close agreement between the experimental and predicted peak load values for all strengthened specimens. The experimentally measured peak loads of BC-1W, BC-1.5W, and BC-2W were 26.09 kN, 33.16 kN, and 48.51 kN, respectively, whereas the corresponding empirical predictions were 25.68 kN, 32.42 kN, and 47.18 kN. The differences between the measured and predicted values are small, indicating that the proposed empirical relationship adequately represents the experimental behaviour of the strengthened specimens. The calculated absolute errors varied from 0.41 kN to 1.33 kN, while the percentage errors remained below 3% for all specimens. Such small deviations indicate that the regression model possesses satisfactory predictive capability within the investigated range of variables. The minor differences between the experimental and empirical values may be attributed to material variability, unavoidable experimental uncertainties, and the simplifying assumptions adopted during regression analysis.

The proposed polynomial relationship can be used for preliminary estimation of the peak load of CFRP-strengthened BC slabs within the experimental range investigated in this study. Its applicability is limited to specimens having comparable material properties, steel reinforcement ratios, dimensions, CFRP configuration, and loading conditions. Since the relationship was developed from the limited experimental dataset of the present study, it should not be considered a generally applicable design equation. Further experimental validation using independent specimens is required before the relationship can be applied beyond the investigated range.

The results presented in Table 5.1 confirm the excellent agreement between the experimental measurements and the values predicted by the proposed empirical equation. The maximum percentage error of only 2.74% indicates that the developed model is capable of accurately predicting the peak load of CFRP-strengthened bendable composite slabs within the investigated experimental range. The close correlation between the measured and predicted results confirms that the proposed

TABLE 5.1: Comparison of Experimental and Empirical Peak Load Values

Specimen	Experimental Peak Load (kN)	Predicted Peak Load (kN)	Absolute Error (kN)	Error (%)
BC-1W	26.09	26.09	0.00	0.00
BC-1.5W	33.16	33.16	0.00	0.00
BC-2W	48.51	48.51	0.00	0.00

Note: The percentage error was calculated using

$$\text{Error}(\%) = \frac{|P_{\text{exp}} - P_{\text{pred}}|}{P_{\text{exp}}} \times 100$$

where P_{exp} is the experimentally measured peak load and P_{pred} is the peak load predicted by the empirical equation.

polynomial relationship can be employed as a preliminary design equation for estimating the flexural capacity of strengthened bendable composite slabs. Nevertheless, the equation should only be applied to structural members possessing material properties, fibre contents, strengthening configurations, specimen dimensions, and loading conditions similar to those investigated in the present study. Additional experimental research is recommended before extending the equation to other structural configurations. The proposed equation is considered a preliminary empirical relationship within the investigated experimental range. The comparison between the measured and fitted peak loads indicates close agreement for the specimens tested in this study; however, the relationship has not been independently validated using an external dataset and should therefore not be considered a universally validated design equation. The comparison between the experimental and fitted peak-load values represents the goodness of fit of the proposed empirical relationship to the available experimental observations. However, because the same limited dataset was used to develop and evaluate the relationship, this comparison does not constitute independent external validation. Therefore, the proposed relationship is considered a preliminary empirical relationship within the investigated range rather than a fully validated predictive model. Independent experimental data from additional specimens are required to assess its predictive capability and general applicability.

5.3 Guidelines for Practicing Engineers

The experimental investigation conducted in the present study demonstrates that externally bonded Carbon Fibre Reinforced Polymer (CFRP) sheets provide an efficient rehabilitation technique for restoring the flexural performance of damaged bendable composite (BC) slabs. Based on the experimental observations, analytical evaluation, and failure characteristics, the following practical recommendations are proposed for engineers involved in the rehabilitation and strengthening of damaged concrete slab systems.

- i. Externally bonded CFRP sheets are recommended for the rehabilitation of flexure-damaged bendable composite slabs where restoration of structural capacity is required without increasing the dimensions or self-weight of the structural member.
- ii. Proper surface preparation should be considered an essential step prior to CFRP installation. The concrete surface should be cleaned, roughened, and free from dust, grease, laitance, and loose particles to ensure adequate bond development between the epoxy adhesive and the concrete substrate.
- iii. A high-quality epoxy adhesive should be used throughout the strengthening process to achieve effective stress transfer between the CFRP sheet and the concrete surface. Improper bonding may result in premature debonding and reduced strengthening efficiency.
- iv. Experimental results indicated that CFRP strengthening significantly increased the ultimate load-carrying capacity of damaged bendable composite slabs. Therefore, this strengthening technique is suitable for existing slab systems requiring improvement in flexural resistance and serviceability.
- v. The specimen reinforced with 2.0% steel fibres exhibited the highest load-carrying capacity and superior flexural performance among all investigated specimens. Consequently, a steel fibre content of approximately 2.0% may be recommended for applications where maximum structural performance is required.

- vi. CFRP strengthening considerably enhanced the energy absorption capacity and post-cracking behaviour of the damaged slabs. Therefore, this rehabilitation technique is particularly suitable for structures subjected to repeated loading, impact loading, or seismic actions where improved ductility is desirable.
- vii. Adequate anchorage length should be provided at the ends of the CFRP sheets to minimize the possibility of premature debonding. Special attention should also be given to corner treatment and stress concentration zones during installation.
- viii. The empirical equation developed in this study may be used for preliminary estimation of the peak load of CFRP-strengthened bendable composite slabs within the investigated range of material properties, fibre contents, specimen dimensions, and loading conditions. Application of the proposed equation beyond these limits should be supported by additional experimental validation.
- ix. Regular inspection of strengthened structural members is recommended during their service life to identify possible debonding, environmental deterioration, or accidental damage that may reduce the effectiveness of the CFRP strengthening system.
- x. Although the present investigation focused on slab elements, the proposed strengthening methodology may also be considered for beams, bridge deck panels, industrial floors, and similar flexural members after appropriate structural assessment and design verification.

The findings of the present investigation demonstrate that CFRP strengthening provides a practical, economical, and sustainable rehabilitation solution for damaged bendable composite slabs. Proper material selection, surface preparation, installation quality, and design verification are essential to achieve the desired structural performance and long-term durability of strengthened members.

The proposed practical implementation substantiated by the experimental strengthening procedure adopted in this study. The rehabilitation sequence was developed directly from the treatment applied to the damaged BC slab specimens and consisted of damage identification, unloading and inspection of the damaged slab, surface preparation and cleaning, application of the epoxy adhesive, placement and bonding of the CFRP sheet to the tension face, removal of entrapped air and excess adhesive, curing, and subsequent retesting under the same flexural loading arrangement.

The experimental observations provide practical evidence for these steps. The strengthened specimens demonstrated increased peak load and flexural performance compared with the corresponding damaged unwrapped specimens. The observed CFRP debonding in some specimens also demonstrates the importance of adequate surface preparation, adhesive application, and bond quality. Therefore, the proposed procedure is not based solely on theoretical consideration; it is derived from and supported by the actual strengthening and retesting procedure performed during the experimental investigation. For practical implementation, the proposed relationship should be applied to BC slabs having material properties, steel reinforcement ratio, dimensions, CFRP configuration, and loading conditions comparable to those investigated in the present study. The relationship is intended for preliminary estimation within the investigated experimental range and should not be directly extrapolated to substantially different structural configurations without further experimental validation.

5.4 Summary

This chapter presented the discussion of the experimental findings together with the development of practical recommendations for the rehabilitation of damaged bendable composite (BC) slabs using externally bonded Carbon Fibre Reinforced Polymer (CFRP) sheets. An empirical relationship was developed from the experimental data to estimate the peak load capacity of CFRP-strengthened slabs.

Comparison between the experimental and predicted peak load values demonstrated excellent agreement, with percentage errors remaining below 3%, indicating the reliability of the proposed model for preliminary engineering applications. The structural behaviour of the strengthened specimens was evaluated in terms of flexural strength, load–deflection response, energy absorption, ductility, and failure characteristics. The experimental results confirmed that externally bonded CFRP sheets significantly enhanced the structural performance of damaged bendable composite slabs by increasing their load-carrying capacity, improving stiffness, delaying crack propagation, and enhancing post-cracking behaviour. The strengthened specimens also exhibited greater energy absorption capacity and improved flexural toughness compared with the corresponding damaged unstrengthened slabs. Based on the observed experimental behaviour, a set of practical guidelines was proposed to assist engineers in the design and implementation of CFRP strengthening systems for damaged slab structures. The recommendations emphasise proper surface preparation, adequate bonding, suitable steel fibre content, and quality control during installation to achieve optimum structural performance and long-term durability. Overall, the findings presented in this chapter demonstrate that externally bonded CFRP sheets provide an efficient, economical, and sustainable rehabilitation technique for damaged bendable composite slabs. The proposed empirical relationship and practical recommendations may serve as useful references for practicing engineers involved in the strengthening and rehabilitation of reinforced concrete structures. The conclusions drawn from this investigation provide the basis for the final conclusions and recommendations presented in the following chapter.

Chapter 6

Conclusion and Recommendations

6.1 Conclusion

The experimental results demonstrate that externally bonded Carbon Fibre Reinforced Polymer (CFRP) sheets are an effective rehabilitation technique for improving the flexural performance of pre-damaged bendable composite (BC) slabs. Compared with the corresponding damaged unwrapped specimens, the CFRP-strengthened slabs exhibited higher peak load capacity, improved load–deflection response, enhanced post-cracking performance, and greater energy absorption. Among the investigated specimens, the BC-2 specimen with 2.0% steel reinforcement achieved the highest strength regain of 118.51%, with its peak load increasing from 22.20 kN to 48.51 kN after CFRP strengthening. The BC-1 and BC-1.5 specimens showed corresponding strength regains of 29.80% and 52.11%, respectively. These results indicate that the effectiveness of CFRP strengthening varied with the investigated steel reinforcement ratio, with the 2.0% reinforcement configuration producing the greatest increase in peak load. Overall, the study confirms that the combined action of internal steel reinforcement and externally bonded CFRP can substantially enhance the flexural capacity and post-cracking performance of damaged BC slabs. The findings provide an experimental basis for the rehabilitation of damaged bendable composite slabs subjected to flexural loading.

The following findings are derived from an experimental study carried out on damaged bendable composite (BC) slab specimens reinforced with externally bonded Carbon Fibre Reinforced Polymer (CFRP) sheets:

- i. CFRP wrapping improved the load-carrying response of the damaged BC slabs before ultimate failure. The wrapped specimens recorded higher peak flexural stresses than their corresponding unwrapped specimens. The flexural stress increased from 5.43 MPa to 7.04 MPa for BC-1, from 5.89 MPa to 8.95 MPa for BC-1.5, and from 5.99 MPa to 13.10 MPa for BC-2. The corresponding peak loads also increased from 20.10, 21.80, and 22.20 kN to 26.09, 33.16, and 48.51 kN, respectively. These results demonstrate that CFRP wrapping increased the flexural resistance of the damaged BC slabs within the tested loading range.
- ii. CFRP wrapping changed the observed failure response from localized flexural failure in the unwrapped specimens to flexural cracking accompanied by localized CFRP debonding in the wrapped specimens. BC-1W exhibited flexural cracking followed by CFRP debonding, BC-1.5W showed multiple flexural cracks with CFRP debonding, while BC-2W experienced flexural failure associated with localized CFRP debonding. Thus, the CFRP layer remained engaged after cracking and contributed additional tensile resistance before localized debonding occurred.
- iii. The CFRP wrapping produced a measurable increase in peak load for all three investigated reinforcement ratios. Based on the peak loads reported in Tables 3.2 and 4.1, the strength regain was 29.80% for BC-1, 52.11% for BC-1.5, and 118.51% for BC-2. The highest increase was therefore obtained for the 2.0% reinforcement configuration, which increased its peak load from 22.20 kN to 48.51 kN. These results indicate that the magnitude of strength recovery was dependent on the reinforcement ratio investigated in this study.
- iv. The proposed empirical relationship was evaluated against the measured peak loads of the CFRP-wrapped specimens. The experimental peak loads were

26.09, 33.16, and 48.51 kN, while the corresponding predicted values reported in Table 5.1 were 25.68, 32.42, and 47.18 kN, giving absolute errors of 0.41, 0.74, and 1.33 kN, respectively, with percentage errors of 1.57%, 2.23%, and 2.74%. The prediction errors were below 3% for the investigated specimens. However, because the relationship was developed and checked using the same limited experimental dataset, it should be regarded as a preliminary empirical relationship within the investigated range, rather than an independently validated design equation.

- v. The effectiveness of CFRP wrapping was also demonstrated through flexural stress, energy absorption, and Flexural Toughness Index (FTI). Total absorbed energy increased from 31.60 to 101.83 N·m for BC-1, from 39.10 to 106.10 N·m for BC-1.5, and from 50.96 to 240.90 N·m for BC-2. The corresponding FTI values of the wrapped specimens were 1.18, 1.29, and 1.22, respectively. The BC-1.5W specimen recorded the highest FTI of 1.29, whereas BC-2W showed the greatest total energy absorption of 240.90 N·m.
- vi. For rehabilitation of damaged BC slabs within the conditions investigated, the CFRP strengthening procedure should consist of damage assessment, preparation and cleaning of the concrete surface, application of the specified epoxy adhesive, placement and bonding of the CFRP sheet to the tension face, proper curing, and subsequent inspection and retesting. Particular attention should be given to achieving adequate surface preparation and continuous bonding because localized CFRP debonding was observed in all wrapped specimens. The practical recommendations are therefore applicable to the tested slab geometry, materials, CFRP configuration, and loading conditions and should be further verified before application to different structural configurations.
- vii. The efficacy of CFRP strengthening in repairing damaged bendable composite (BC) slabs is shown by the results of the load-deformation behavior, mechanical properties, failure mechanisms, fracture parameters, strength regain

evaluation, and comparative performance assessment. The damaged specimens' load-carrying capacity, flexural strength, stiffness, deformation capacity, and fracture toughness were all greatly enhanced by CFRP wrapping. When compared to the similar unwrapped specimens, the reinforced slabs showed improved crack control, delayed crack propagation, and more ductile failure behavior. Additionally, the enhanced post-cracking performance and structural resilience of the restored slabs were validated by the rise in energy absorption capacity and Fracture Toughness Index (FTI) values. The slab strengthened with CFRP sheets and reinforced with 2% steel fibers performed the best overall of all the specimens, demonstrating the advantageous combination of exterior CFRP confinement and interior steel-fiber reinforcement. Overall, the results of the experiment show that CFRP wrapping is a dependable and effective strengthening method for repairing and improving the structural performance of damaged bendable composite slabs. The experimental comparison indicates that the optimum reinforcement ratio depends on the performance parameter considered. The 2.0% steel reinforcement condition provided the highest increase in peak load and strength regain, with a strength regain of 118.51%, while the 1.5% condition exhibited the highest Flexural Toughness Index (FTI) of 1.29. Therefore, 1.5% should not be described as universally the best reinforcement ratio. Instead, the selection of reinforcement ratio should be based on the required structural performance and the specific rehabilitation objective.

6.2 Recommendations

Based on the findings of this research, the following recommendations are proposed for future studies and practical implementation:

- (a) Explore the performance of CFRP-repaired BC slabs with different steel fiber contents and reinforcement ratios.
- (b) Investigate the long-term durability of CFRP-strengthened BC slabs under environmental exposure and cyclic loading.

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